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EVALUATION OF A CIRCULATION CONTROL TAIL BOOM FOR YAW CONTROL

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Division of the Summa Corporation
Culver City, Calif. 90230

April 1978

Final Report for Period 1 March 1977 - 1 February 1978

Prepared for

APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

Prior design studies by Hughes Helicopters have indicated that an integrated circulation control/direct jet antitorque system can replace the tail rotor of a typical light helicopter without degrading the helicopter performance. Utilizing the data from the design studies, Hughes Helicopters performed static ground tests on an experimental device that demonstrated the potential of the circulation control portion of the circulation control/direct jet antitorque system. The next step in the development cycle was to determine how the circulation control tail boom device would operate during flight. The results of the flight demonstration program are documented in this report. The circulation control tail boom is a concept that can compliment an antitorque device (such as a direct jet) to increase the power available to the main rotor during hover. These experimental results support the prior design studies and demonstrate that circulation control principles can be applied effectively to a helicopter tail boom to produce antitorque force from the main rotor wake.

Mr. Robert P. Smith of the Technology Applications Division, Aeromechanics Technical Area, served as project engineer for this effort.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: USARTL-TR-78-10	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): EVALUATION OF A CIRCULATION CONTROL TAIL BOOM FOR YAW CONTROL.	5. TYPE OF REPORT & PERIOD COVERED: Final Report, 1 Mar[redacted]77 - 1 Feb[redacted]78
	6. PERFORMING ORG. REPORT NUMBER: HH-77-307
7. AUTHOR(s): A.H. Logan	8. CONTRACT OR GRANT NUMBER(s): DAAJ02-77-C-0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Hughes Helicopters, Division of Summa Corporation, Culver City, Ca. 90230	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62209A 1L262209AH76 00 188 EK
11. CONTROLLING OFFICE NAME AND ADDRESS: Applied Technology Laboratory, U.S. Army Research and Technology Labs (AVRADCOM) Fort Eustis, VA. 23604	12. REPORT DATE: Apr[redacted]78
	13. NUMBER OF PAGES: 53
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Circulation Control
Yaw Control Devices
Helicopter
Boundary Layer Blowing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experimental tail boom which uses circulation control principles to produce antitorque force from the main rotor downwash was flight-tested over a typical flight regime. The flight envelope included hover; sideward and rearward flight to 30 knots; forward flight to 80 knots; climbs, turns, and maneuvers, such as pull-ups, and push-overs at 60 knots; and autorotation.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

409 164

20. Abstract - Continued

The circulation control tail boom provides antitorque force by deflecting the main rotor wake. A thin stream of air is ejecting tangential to the tail boom surface from a single slot running the length of the tail boom. The stream of air, in combination with the tail boom shape, deflects the main rotor wake and produces a force in the required antitorque direction.

The flight test demonstrated that circulation control principles can be applied effectively to a helicopter tail boom to provide antitorque force from the main rotor wake. The circulation control tail boom interacted with the main rotor wake in a steady, controllable, and predictable manner. Maximum effectiveness occurred in hover. In maneuvering flight at 60 knots, the circulation control tail boom did not affect the aircraft handling qualities in any maneuver, including autorotation.

In hover, the circulation control tail boom produced 40 pounds of equivalent tail rotor thrust at an approximate three to one power reduction. Including the fan power, the helicopter required 5.5 less horsepower to hover with the circulation control tail boom operating than with it inoperative.

SUMMARY

An experimental tail boom which uses circulation control principles to produce antitorque force from the main rotor downwash was flight-tested over a typical flight regime. The objective of the test was to define the range of flight conditions where circulation control principles may be applied effectively. The flight envelope included hover; sideward and rearward flight to 30 knots; forward flight to 80 knots; climbs, turns, and maneuvers, such as pull-ups, and push-overs at 60 knots; and autorotation.

The circulation control tail boom provides antitorque force by deflecting the main rotor wake. A thin stream of air is ejected tangential to the tail boom surface from a single slot running the length of the tail boom. The stream of air, in combination with the tail boom shape, deflects the main rotor wake and produces a force in the required antitorque direction.

The flight test demonstrated that circulation control principles can be applied effectively to a helicopter tail boom to provide antitorque force from the main rotor wake. The circulation control tail boom interacted with the main rotor wake in a steady, controllable, and predictable manner. The circulation control tail boom was effective at speeds up to 30 knots sideward, 40 knots forward, and 10 knots rearward. Maximum effectiveness occurred in hover. The tail boom effectiveness in rearward flight applies only to the particular boom design tested. The effectiveness was limited by the circulation control slot forward extent, and alternate slot designs would expand the rearward flight effectiveness. In maneuvering flight at 60 knots, the circulation control tail boom did not affect the aircraft handling qualities in any maneuver, including autorotation.

In hover, the circulation control tail boom produced 40 pounds of equivalent tail rotor thrust at an approximate three to one power reduction. Including the fan power, the helicopter required 5.5 less horsepower to hover with the circulation control tail boom operating than with it inoperative.

The flight test demonstrates that the circulation control tail boom can be integrated successfully into a yaw control system that eliminates the tail rotor. In this design, the tail rotor is replaced by a system using the circulation control tail boom and a direct jet. Both the tail boom and jet are supplied with air from a variable-pitch fan mounted inside the fuselage at the forward end of the tail boom.

PREFACE

This report was prepared by Hughes Helicopters, Division of Summa Corporation, under Contract DAAJ02-77-C-0018, funded by the Applied Technology Laboratory (ATL) of the U.S. Army Research and Technology Laboratories (AVRADCOM). It covers the work performed during the period March 1977 to February 1978. It is the final technical report summarizing the activity. The ATL technical monitor for this contract was Robert P. Smith, whose contributions to this program are gratefully acknowledged. The Hughes Helicopters project manager was A. H. Logan, who also prepared the final report.

The author wishes to acknowledge R. E. Moore, Manager, Research and Development Department, and E. R. Wood, Manager of Technical Analysis, for their support and encouragement during the program. The author also wishes to acknowledge the following Hughes personnel: R. Marthe, who designed the circulation control tail boom and managed the aircraft preparation up to flight test; S. Dorris and J. Bardell, who were responsible for flight testing; J. Zimmerman, who was the test pilot; C. L. Marshall and P. J. Vercammen, who were the instrumentation engineers; D. Mancill, who did the stress analysis; and S. V. LaForge, who performed the data reduction and supporting analysis.

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INTRODUCTION

Circulation control has been the subject of a considerable amount of research over the past years. This research[1, 2, 3, 4] has defined a wide and consistent body of data which demonstrates the large force generation potential of circulation control, and defines the important parameters that control its effective application. Using these data, circulation control principles have been applied to the wings of fixed-wing aircraft[5] and the main rotor blades of helicopters.[6] These applications have shown that the use of circulation control promises significant improvements in maximum lift and in operating economies, particularly when applied to helicopters. In addition to the main rotor blades of helicopters, circulation control offers potential benefits when used to generate the antitorque force needed by helicopters. For this use, circulation control is applied to the helicopter tail boom to convert the main rotor wake into an antitorque force.

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[1] Lockwood, V. E., LIFT GENERATION ON A CIRCULAR CYLINDER BY TANGENTIAL BLOWING FROM SURFACE SLOTS, National Aeronautics and Space Administration Technical Notice D-244, May 1960.

[2] Cheesman, I. C., THE APPLICATION OF CIRCULATION CONTROL BY BLOWING TO HELICOPTER ROTORS, Journal of the Royal Aeronautical Society, Volume 71, Number 679, July 1967.

[3] Wygnanansky, I., and Newman, B. G., THE EFFECT OF JET ENTRAINMENT ON LIFT AND MOMENT FOR A THIN AIRFOIL WITH BLOWING, Aeronautical Quarterly, Volume XV, Part 2, May 1964.

[4] Stone, M. B., and Englar, R. J., CIRCULATION CONTROL – A BIBLIOGRAPHY OF NSRDC RESEARCH AND SELECTED OUTSIDE REFERENCES, Naval Ship Research and Development Center Report 4108, January 1974.

[5] Englar, R. J., TWO-DIMENSIONAL TRANSONIC WIND TUNNEL TESTS OF THREE 15 PERCENT-THICK CIRCULATION CONTROL AIRFOILS, Naval Ship Research and Development Center Technical Note AL-182, AD 882-075, December 1970.

[6] Williams, R. M., SOME RESEARCH ON ROTOR CIRCULATION CONTROL, Third CAL/AVLABS Symposium on Aerodynamics of Rotary Wing and V/STOL Aircraft, June 1969.

The circulation control tail boom provides antitorque force by deflecting the main rotor wake (Figure 1). A thin stream of air is ejected tangential to the tail boom surface from a slot running the length of the tail boom. The stream of air, in combination with the tail boom shape, deflects the main rotor downwash and produces a force in the required antitorque direction.

The most significant potential helicopter application of circulation control is the development of an integrated system that eliminates the helicopter tail rotor. Design studies have indicated that an integrated, circulation-control/direct-jet, antitorque system can replace the tail rotor of a typical light helicopter without degrading the helicopter performance. The power requirements of the circulation-control/direct-jet system in sideward flight have been compared to the tail rotor. In these flight conditions, the peak power required by the circulation-control/direct-jet system is no greater than the tail rotor. This indicates that sideward flight maneuvers, now performed by the OH-6A with a tail rotor, will not be limited by replacing the tail rotor by the circulation-control/direct-jet system.

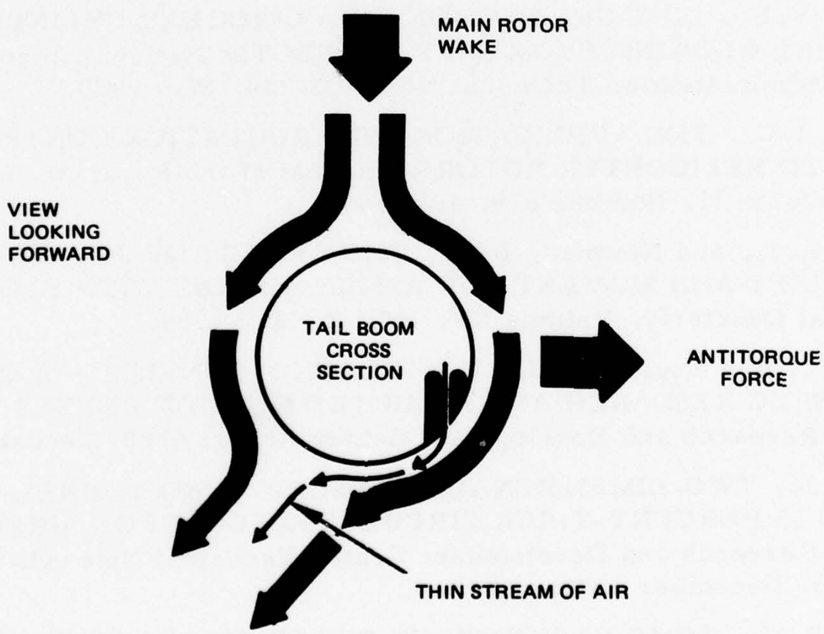

Figure 1. The Circulation Control Tail Boom Provides Antitorque Force From the Main Rotor Wake.

An area of concern is how the circulation control tail boom would behave in flight due to the unsteady and highly turbulent main rotor wake of an actual helicopter. This flow state contrasts sharply with the steady, low turbulence, wind tunnel conditions under which previous circulation control data were recorded. Also, since the circulation control tail boom deflects the main rotor wake to produce an antitorque force, wake movement induced by forward, rearward, or sideward flight would affect its ability to produce that force. There is a flight speed when the wake will be off the tail boom completely, rendering circulation control ineffective. Rotor wake locations and strengths are difficult to estimate analytically, particularly in the low-speed flight regime below 30 knots.

An experimental tail boom which uses circulation control principles to produce an antitorque force from the main rotor downwash was flight-tested over a typical flight regime. The object of the test was to define the range of flight conditions where circulation control principles may be applied effectively to produce an antitorque force. Particular attention was given to forward, rearward, and sideward flight to 40 knots, as well as hover and vertical climb capability.

The OH-6A was the baseline aircraft, and the circulation control tail boom was designed around the basic OH-6A tail boom. Circulation control air was provided by a fixed-pitch electrical fan powered by the existing OH-6A starter-generator. The modified OH-6A retained the tail rotor for all flight conditions. The horizontal and vertical stabilizers were removed so that tail rotor thrust could be measured directly by tail boom bending.

The ability of the circulation control tail boom to provide an effective antitorque force was determined by the thrust requirements of the tail rotor. The modified OH-6A was flown with and without circulation control blowing, and tail rotor thrust requirements were compared at equivalent flight conditions. Tail rotor drive shaft torque and tail rotor pedal position were also recorded and compared as supporting measurements of circulation control effectiveness.

The results of the flight test were used to evaluate the aircraft performance benefits and/or penalties that would be associated with the use of the circulation control tail boom, both with and without a tail rotor. A suggested design of the integrated, circulation-control/direct-jet, yaw control system is presented and discussed.

DESCRIPTION OF TEST AIRCRAFT

TAIL BOOM DESIGN

The general installation of the circulation control tail boom on the OH-6A is presented in Figures 2 and 3. The stabilizers were removed, but the tail rotor was retained. The circulation control tail boom installation consisted of a fan, interconnecting duct, and the circulation control tail boom itself. The fan was mounted aft and below the main rotor and was offset from the helicopter centerline. A fiberglass inlet was attached to the fan intake. A fiberglass interconnecting duct directed the air from the fan to the circulation control tail boom, dumping the air into the annular chamber formed by the outer circulation control skin and the basic OH-6A tail boom. The circulation control tail boom had a circular cross section formed by wrapping a thin metal skin around the basic OH-6A tail boom and attaching it with Z-brackets (Figure 4). The unaltered OH-6A tail boom remained as the load-carrying member. When the air entered the annular chamber, it was diffused, converted to pressure, and ejected out of the slot.

The slot was formed by wooden liners attached to the circulation control skin (Figure 4). The width of the slot was held constant by five spacers distributed along the slot length of the tail boom. An endplate was added at each end of the slot (Figure 5) to prevent spanwise flow.

The fan was a vane-axial, fixed-pitch, electrical fan powered by the existing starter-generator and battery aircraft power system. The fan was chosen to provide, including losses, a pressure of 10.8 inches of water in the tail boom annular chamber at a flow rate of 1050 cubic feet per minute. During operation, the fan absorbed most of the capability of the aircraft power system. Consequently, five additional batteries were installed to supply aircraft power during fan operation. A switching system was used so that when the fan was off, aircraft power was supplied by the aircraft generator-battery system and there was no power drain on the additional batteries. Fan operation was controlled remotely by an on-off switch installed in the cockpit. Each battery was a standard OH-6A Ni-Cd battery with a 13 ampere-hour rating.

The circulation control tail boom had a single slot in the outer sheet metal skin. The slot, a quarter-inch wide and 46 inches long, started at Station 200 which is 2 inches aft of the tail boom attachment point. The slot was on the right side of the aircraft and 140 degrees down from the tail boom top centerline. The boom diameter was 18.1 inches at Station 200 and tapered linearly to 15 inches at the slot end.

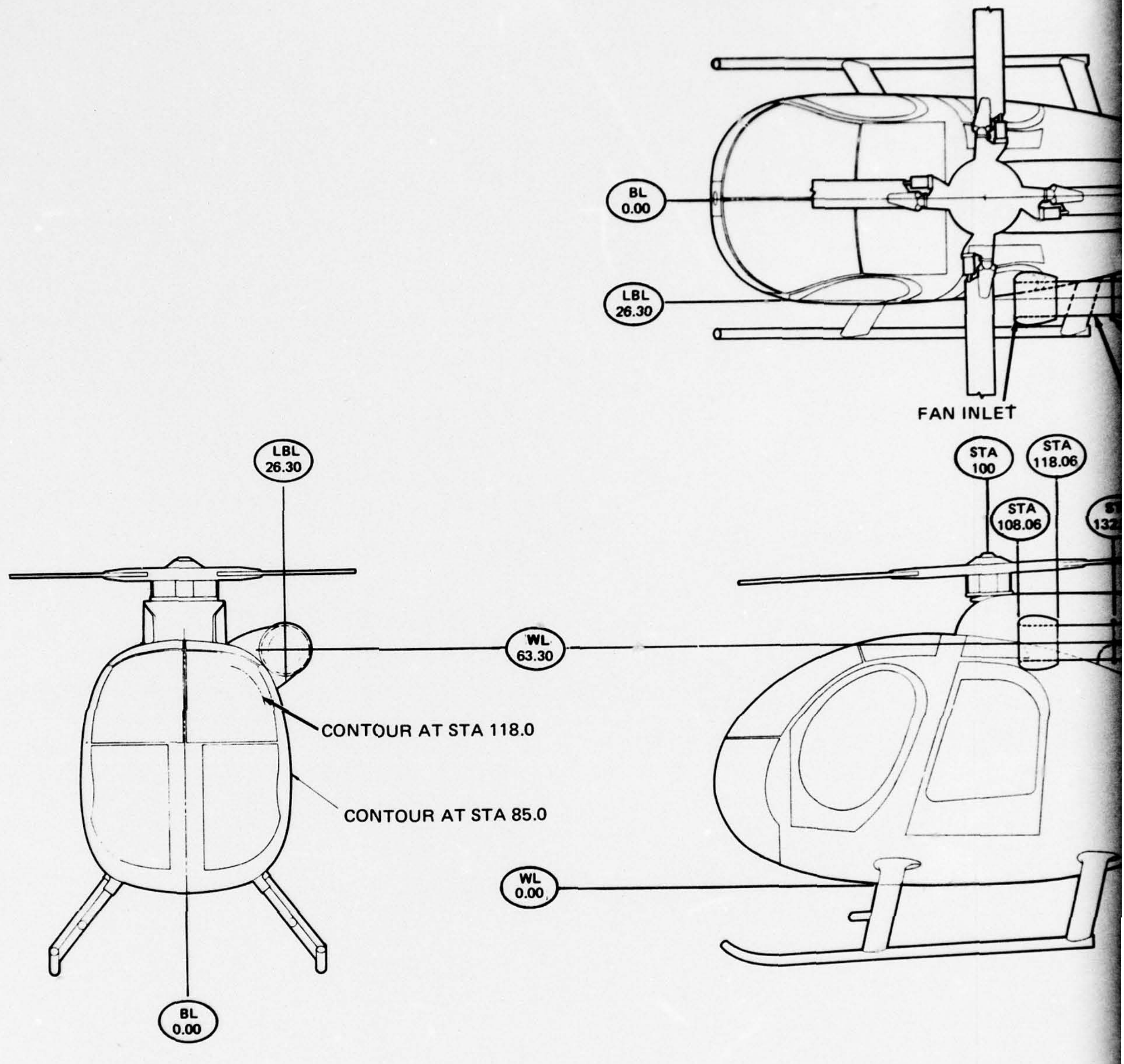

Figure 2. Circulation Control
Tail Boom Installation.

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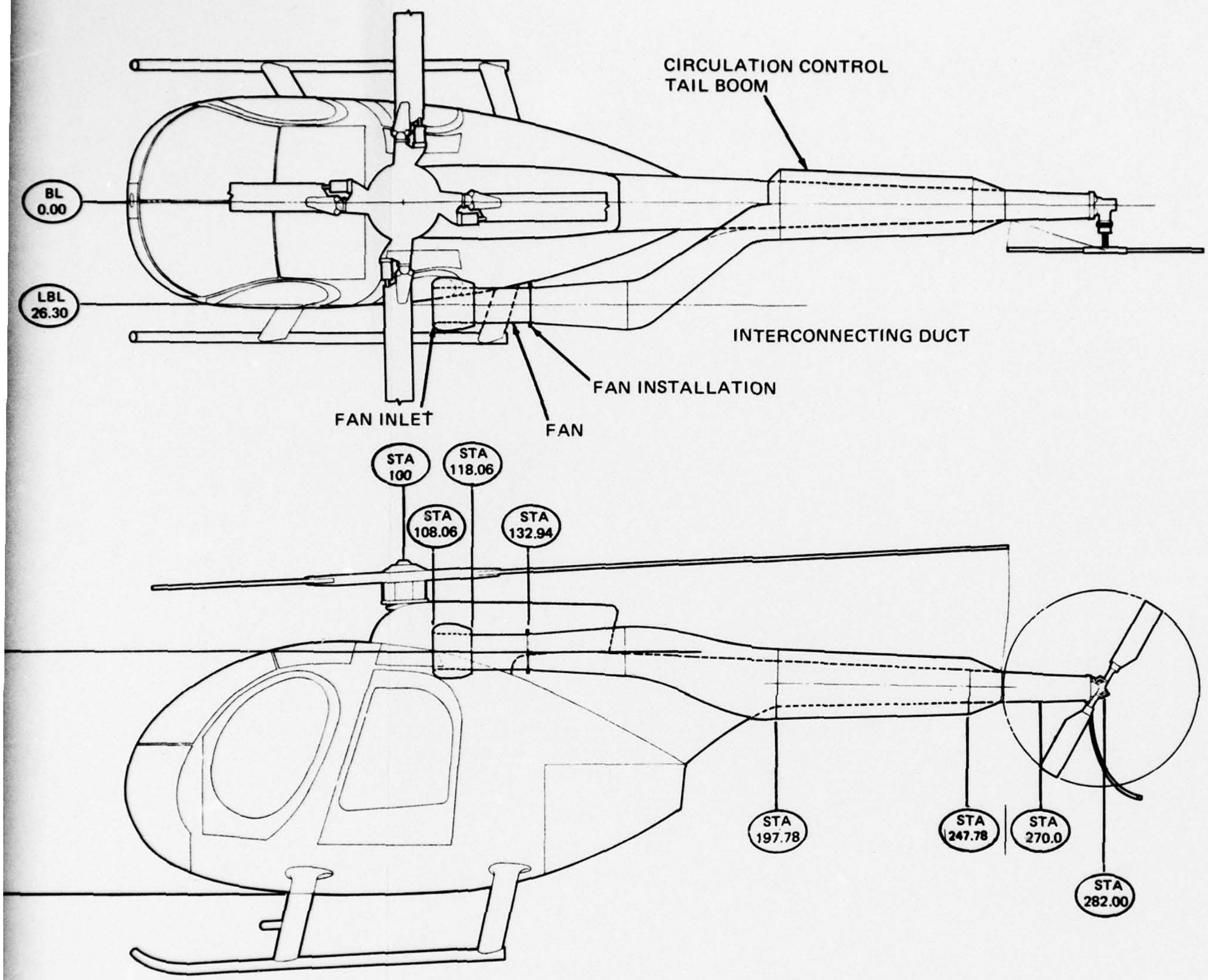

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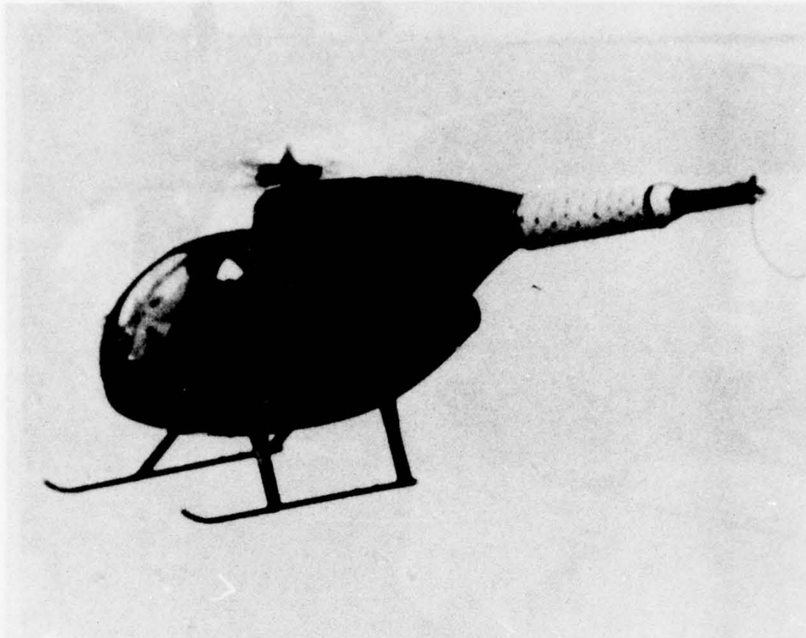

Figure 3. Circulation Control Tail Boom Installed on OH-6A.

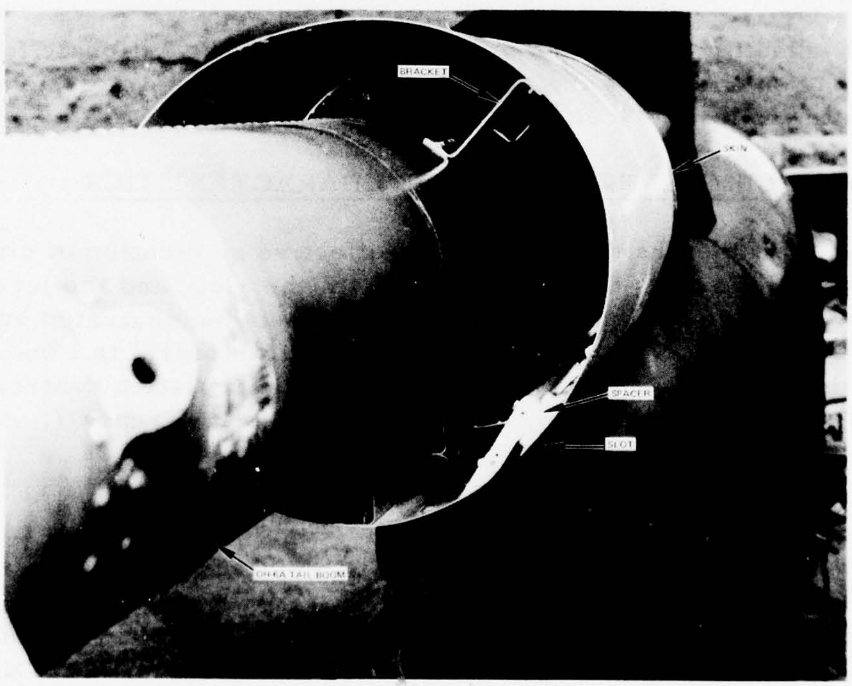

Figure 4. Attachment of Circulation Control Skin to OH-6A Tail Boom.

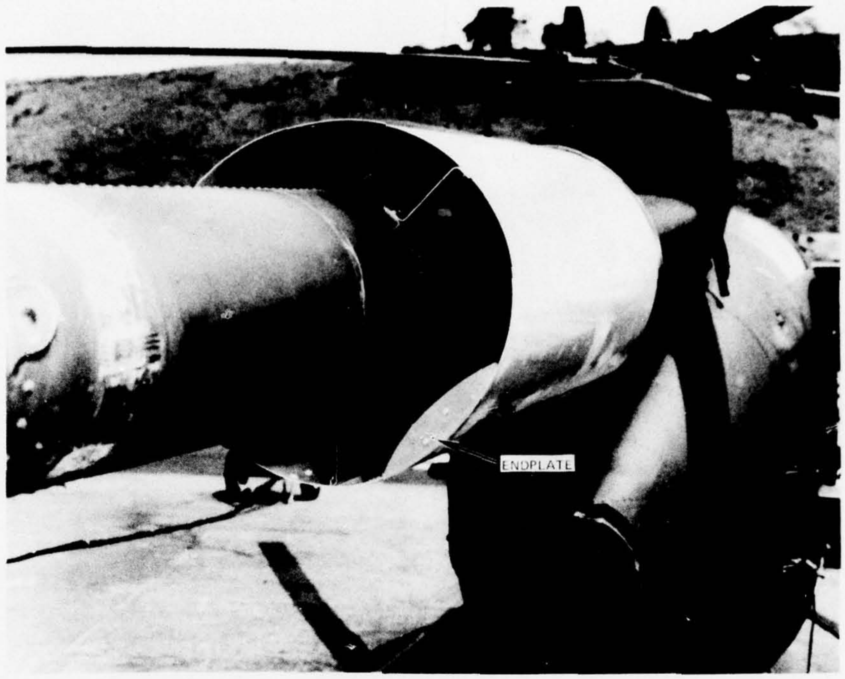

Figure 5. Circulation Control Skin with Slot Endplate.

The aircraft takeoff gross weight was 2415 pounds. The rationale for the selection of the specific slot angle, slot width, and internal pressure is presented in the following section.

SELECTION OF CIRCULATION CONTROL CHARACTERISTICS

The important parameters that control the effective application of circulation control are the slot angle, the jet velocity from the slot, and the jet momentum. The importance of these parameters has been demonstrated both in wind tunnel tests[1] and in application to a circulation control tail boom under a statically thrusting main rotor.[7] The flight test circulation control tail boom design is an extension of the design work reported in Reference 7.

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[7] Logan, A. H., and Niji, K. K., EXPERIMENTAL INVESTIGATION OF A CIRCULATION CONTROL TAIL BOOM UNDER A STATICALLY THRUSTING OH-6A MAIN ROTOR, Hughes Helicopters Report 150-A-2001, February 1976.

As reported in Reference 7, a circulation control test rig was built around a basic OH-6A tail boom and was mounted under the OH-6A main rotor in the position occupied by the basic tail boom. The circulation control tail boom and the main rotor were mounted on the Hughes Helicopters' rotor tracking stand (Figure 6) at a height of one rotor diameter above the ground, thus placing it in an out-of-ground-effect (OGE) condition. Hover-in-ground-effect (HIGE) was simulated by building an artificial ground plane on the work platform a third of a rotor diameter beneath the rotor.

Full-scale test conditions covered both in- and out-of-ground-effect hover for blade collective pitch settings up to 10 degrees. Conditions tested covered jet velocities from 120 to 223 feet per second, slot widths from 0.170 to 0.75 inch, and slot angular locations from 90 to 150 degrees away from the downwash flow direction.

At each test condition, the flow around and on the tail boom surface, both upstream and downstream of the slot location, was visualized with tufts. The tufts provided a visual check of the successful functioning of the circulation control blowing. For successful operation, the tufts showed a smooth, orderly turning of the main rotor downwash about the tail boom and the absence of separation both upstream of the slot and downstream of the slot for approximately 45 degrees.

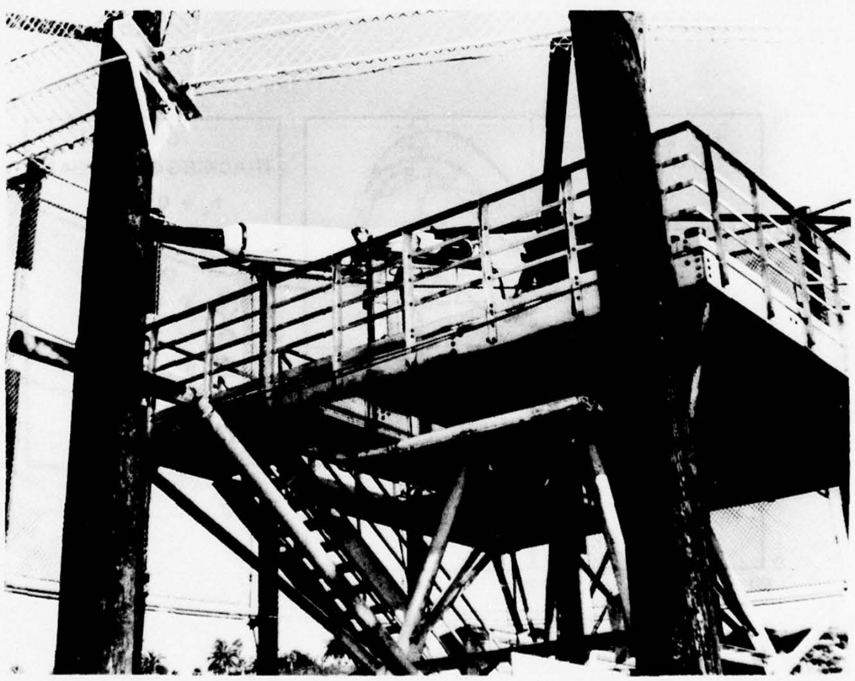


Figure 6. Circulation Control Tail Boom Installed on Whirl Stand.

The data collected provided a basis for selecting the key circulation control parameters. The effects of slot angle, jet velocity, and jet momentum are presented in Figures 7, 8, and 9. Figure 7 presents the mean lateral circulation control gauge force as a function of slot angle for several collective pitch settings. Due to the instrumentation location, the ratio of equivalent tail rotor thrust to gauge force is four to one. As can be seen, the maximum circulation control force was generated at a slot angle of 140 degrees, which was chosen for the flight test configuration.

The effect of jet velocity is shown in Figure 8. In this figure, the ratio of measured and predicted circulation control lateral force is presented as a function of the ratio of jet velocity and maximum downwash in the plane of the tail boom. The predicted force was calculated from an analysis which used a strip-integration procedure to combine the measured local downwash at the boom centerline, the local dimensions of the tail boom, the measured jet velocity and slot configuration, and the two-dimensional wind tunnel data on circulation control cylinders presented in Reference 7. These values were numerically integrated to give the forces on the tail boom.

As can be seen, at a velocity ratio below 3.5, the measured circulation control force is sharply less than what would be expected from wind tunnel data. Above a ratio of 3.5, the circulation control tail boom produces as much force as would be expected. Since the fan power required increases

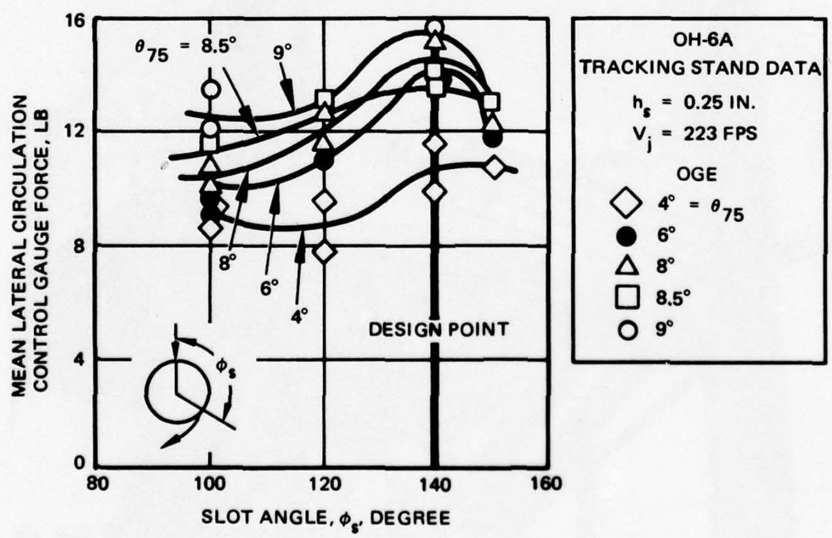


Figure 7. Effect of Slot Location on Circulation Control Force.

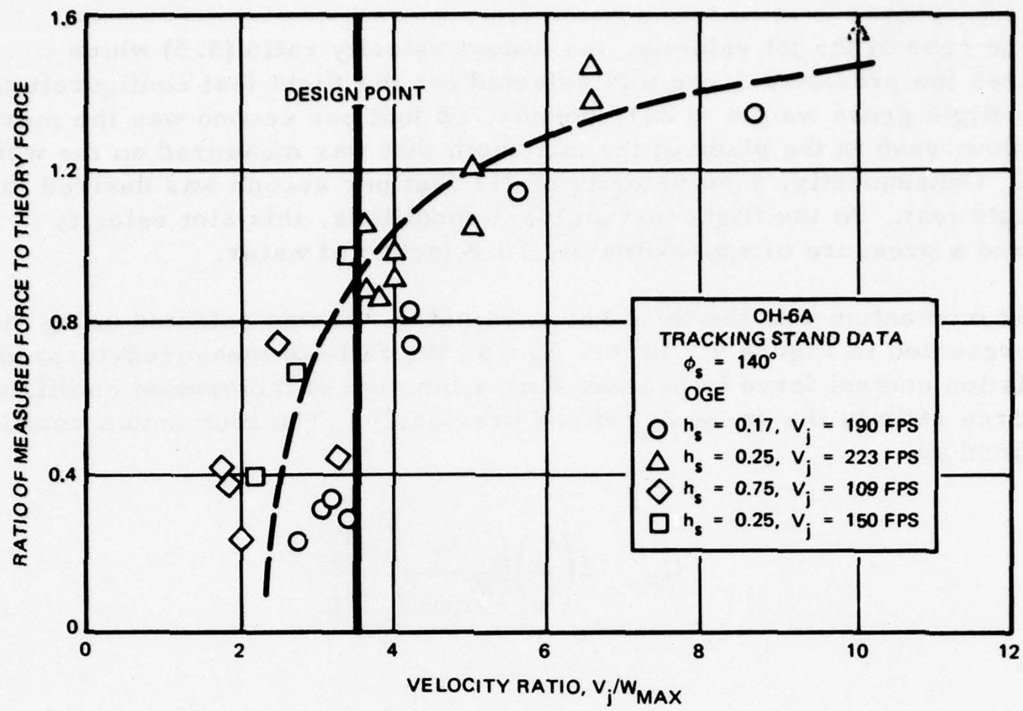


Figure 8. Effect of Velocity Ratio on Circulation Control Force.

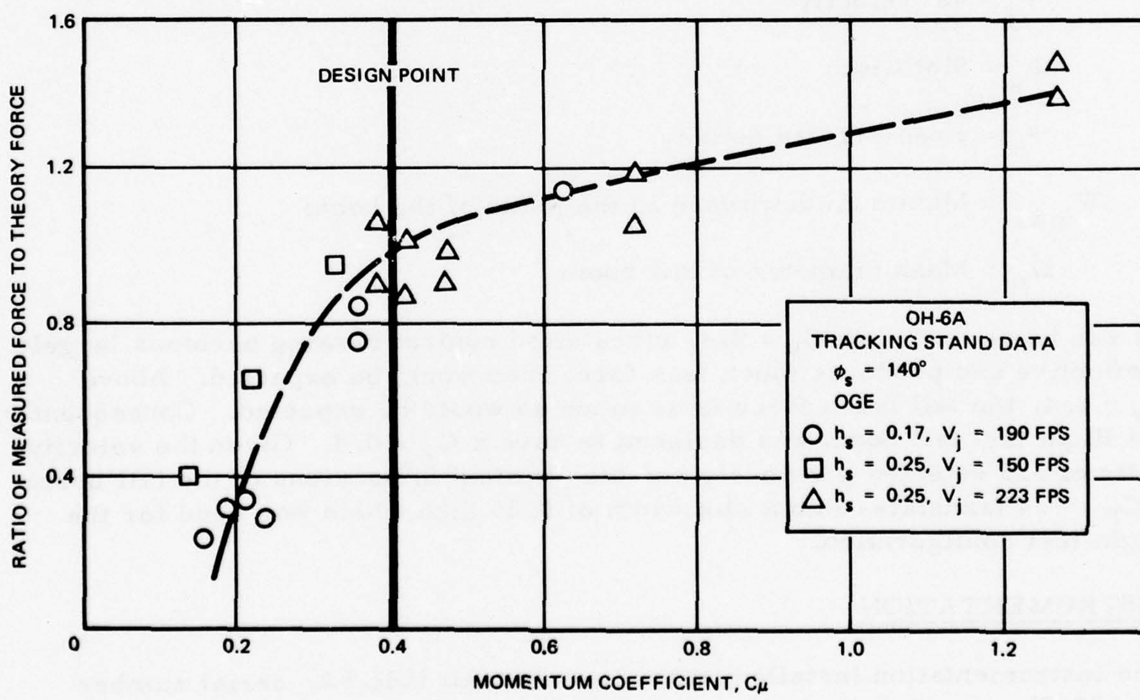


Figure 9. Effect of Momentum Coefficient on Circulation Control Force.

with the cube of the jet velocity, the lowest velocity ratio (3.5) which produces the predicted force was selected for the flight test configuration. At the flight gross weight of 2415 pounds, 62 feet per second was the maximum downwash in the plane of the tail boom that was measured on the whirl stand. Consequently, a jet velocity of 217 feet per second was desired for the flight test. At the flight test ambient conditions, this slot velocity required a pressure of approximately 10.8 inches of water.

The jet momentum was the third key parameter. It was selected using the data presented in Figure 9. In this figure, the ratio of measured-to-predicted circulation control force is presented as a function of momentum coefficient. The force ratio is the same as defined previously. The momentum coefficient is defined as

$$C_\mu = 2\left(\frac{\rho_j}{\rho_\infty}\right)\left(\frac{V_j}{W_{max}}\right)^2 \frac{h_s}{D_B}$$

where

ρ_j = Jet density

V_j = Jet velocity

h_s = Slot width

ρ_∞ = Free-stream density

W_{max} = Maximum downwash in the plane of the boom

D_B = Mean diameter of tail boom

As can be seen, below $C_\mu = 0.4$, circulation control blowing becomes largely ineffective and produces much less force than would be expected. Above $C_\mu = 0.4$, the tail boom force is as much as would be expected. Consequently, the flight test tail boom was designed to have a $C_\mu = 0.4$. Given the velocity ratio of 3.5 selected previously and the physical dimensions of the tail boom, a $C_\mu = 0.4$ translates into a slot width of 0.25 inch which was used for the flight test configuration.

INSTRUMENTATION

The instrumentation installed on the test aircraft (OH-6A, serial number 65-12917) was concerned primarily with evaluating the effectiveness of the

circulation control tail boom. The following list details the parameters to be measured along with the instrumentation to be used to measure the parameter:

a. Tail rotor thrust - strain gauges measuring tail boom lateral bending at Station 270

b. Tail rotor power - tail rotor drive shaft torque and rpm

c. Main rotor power - main rotor drive shaft torque and rpm

d. Tail boom torsion - strain gauges at two stations, approximately Stations 212 and 270

e. Tail boom lateral force - strain gauges at two stations, approximately Stations 212 and 270

f. Fan volume flow rates - fan inlet static temperatures and pressures

g. Fan power - fan input voltage and current

h. Circulation control plenum static pressures - pressure orifices at Stations 211, 225, and 240

i. Circulation control plenum static temperatures - gauges at Stations 211, 225, and 240

j. Recording rate gyros for pitch, roll, and yaw

In addition to these parameters, the flight control (longitudinal cyclic, lateral cyclic, collective, and pedal) positions were recorded as well as airspeed.

Tail rotor thrust and tail boom forces were measured by strain gauges applied to the skin of the basic OH-6A tail boom at Stations 270 and 211. Since the OH-6A tail boom is a monocoque structure, it acts as a load cell and all forces are reacted as strain in the skin. Tail boom strain at Station 270 is outboard of all circulation control skin elements and 12 inches inboard of the tail rotor axis (for reference, see Figure 2). Since all stabilizers are removed, strain at Station 270 measures tail rotor thrust directly. Boom bending strain at Station 212 measures both the circulation control force and the tail rotor thrust.

The strain gauges were calibrated in place on the helicopter by applying weights to the tail boom. All instrumentation had current calibration.

FLIGHT TEST CONDITIONS AND PROCEDURES

The flight test conditions are presented in the following table. The flight conditions include ground tiedown tests; hover; sideward, rearward, and forward flight; critical azimuth; and maneuvers such as climbs, pull-ups, push-overs, forward speed turns, and autorotations. The ground tiedown tests consisted of collective pitch sweeps at an overload gross weight of 3000 pounds. Testing was limited to a light-on-the-skids condition. No vibration was observed in the circulation control skin, duct, or fan attachment. The flight envelope was restricted to 80 knots forward speed due to the removal of the stabilizers.

The maneuver load factors were kept comfortably within the capability of the OH-6A. Pull-ups and turns were done at 1.5g, and the push-overs were done at 0.5g. The identification of the critical azimuth consisted of 10- and 20-knot flights with varying amounts of nose-left yaw. Approximately 20 degrees of nose left is the critical azimuth for the basic OH-6A with stabilizers.

The general flight procedure was to fly a particular condition with the circulation control fan turned off, then immediately repeat that particular flight condition with the circulation control fan on. For example, right sideward

FLIGHT TEST CONDITIONS

Flight Condition	Speed (kn)								
	0	10	20	30	40	50	60	70	80
Ground Tiedown	◇								
Hover, IGE	◇								
Turns	◇								
Hover, OGE	◇								
Turns	◇								
Right Sideward		◇	◇	◇					
Left Sideward		◇	◇	◇					
Forward		◇	◇	◇	◇	◇	◇	◇	◇
Rearward		◇	◇	◇					
Identification of Critical Azimuth		◇	◇						
Maximum Climb	◇						◇		
Maneuver Load Factor									
Pull-ups							◇		
Push-overs							◇		
Turns							◇		
Rate of Descent (Autorotation)							◇		

flight was flown from hover to 30 knots with the fan off. The aircraft returned to hover, turned the fan on, then repeated right sideward flight from hover to 30 knots. In-ground-effect conditions were flown at a nominal 10-foot skid height and out-of-ground-effect conditions were 1.5 rotor diameters above the ground. Sideward, rearward, and forward flight were flown at a nominal 10-foot skid height. Climb flight was done at maximum continuous power.

DISCUSSION OF FLIGHT TEST RESULTS

CIRCULATION CONTROL TAIL BOOM OPERATION

The input aerodynamic blowing characteristics of the circulation control tail boom were essentially constant throughout the flight program. The fan drew approximately 96.5 amperes at 24.7 volts direct current regardless of the flight condition (Figure 10). This current-voltage combination is equivalent to 3.2 electrical horsepower. The fan inlet flow was measured by four static pressure taps and four thermocouples distributed equally about the inlet circumference. Unfortunately, the temperature measurements were not recorded due to equipment failure. The inlet pressures are presented in Figure 11. The data indicate that the pressures are relatively uniform around the inlet circumference. In left sideward and forward flight, inlet ram pressure is evident. However, as is shown in Figure 12, the tail boom plenum pressures did not reflect the inlet pressure variations. This is significant in that the plenum pressures control the slot flow and consequently, the circulation control effect. The disparity between the inlet and plenum pressures indicates that the inlet pressure readings may include unsteady entry effects.

The flow out of the slot was also unaffected by flight condition. The static pressures inside the circulation control tail boom were approximately 10.8, 11.2, and 10.9 inches of water at Stations 211, 225, and 240, respectively (Figure 12). These values remained constant both for flying conditions and for fan-only conditions with the main rotor stopped. With the main rotor stopped and circulation control blowing on, the flow out of the slot was examined both qualitatively and quantitatively. A tuft survey of the slot flow indicated that the slot flow was directed circumferentially with only slight spanwise flow evidenced within 1.5 inches of both ends of the slot. A hot-wire survey of the slot flow indicated that the slot velocity varied approximately 2 percent over the length of the slot. Based on the plenum pressures and slot geometry, the flow rate was relatively steady at 1050 cfm. Based on the jet velocity and flow rate, the aerodynamic blowing power was 1.8 horsepower.

The effect of circulation control blowing on tail boom flow quality during flight was evidenced by the tufts applied to the tail boom surface. Figure 13 shows the flow quality in a hover both with and without circulation control effect. The same general flow changes were shown at flight conditions other than hover. Flow quality with fan off is shown in the left view of Figure 13. The tufts show a separation upstream of the slot at approximately 120 degrees down from the top centerline (the thin horizontal line is the circulation control slot). The flow quality changes dramatically with the fan on as shown in the

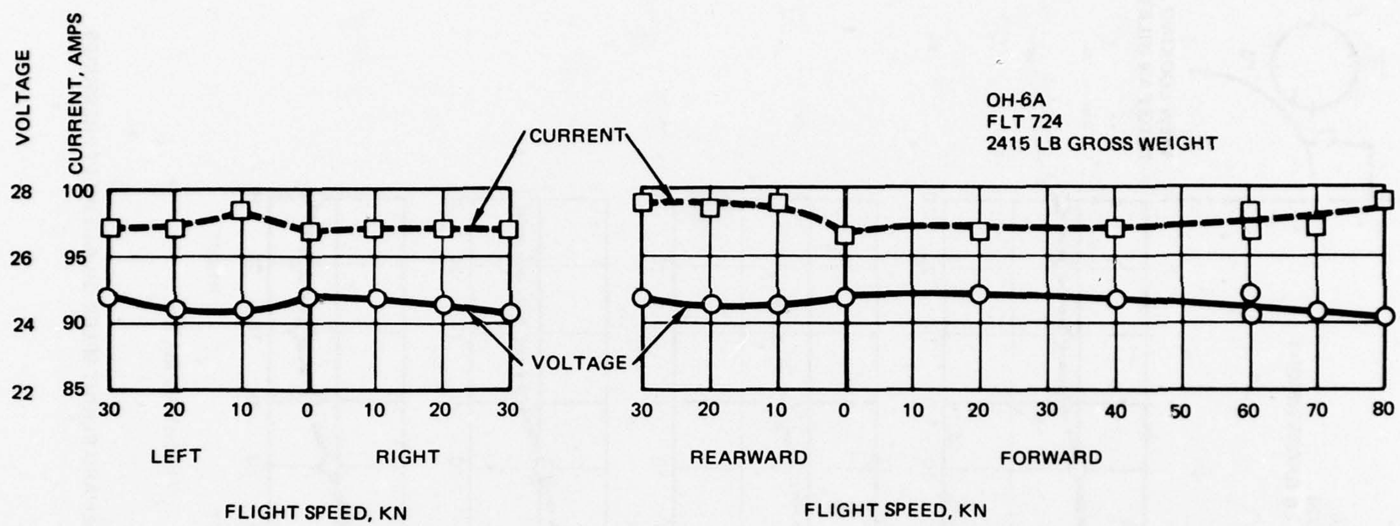
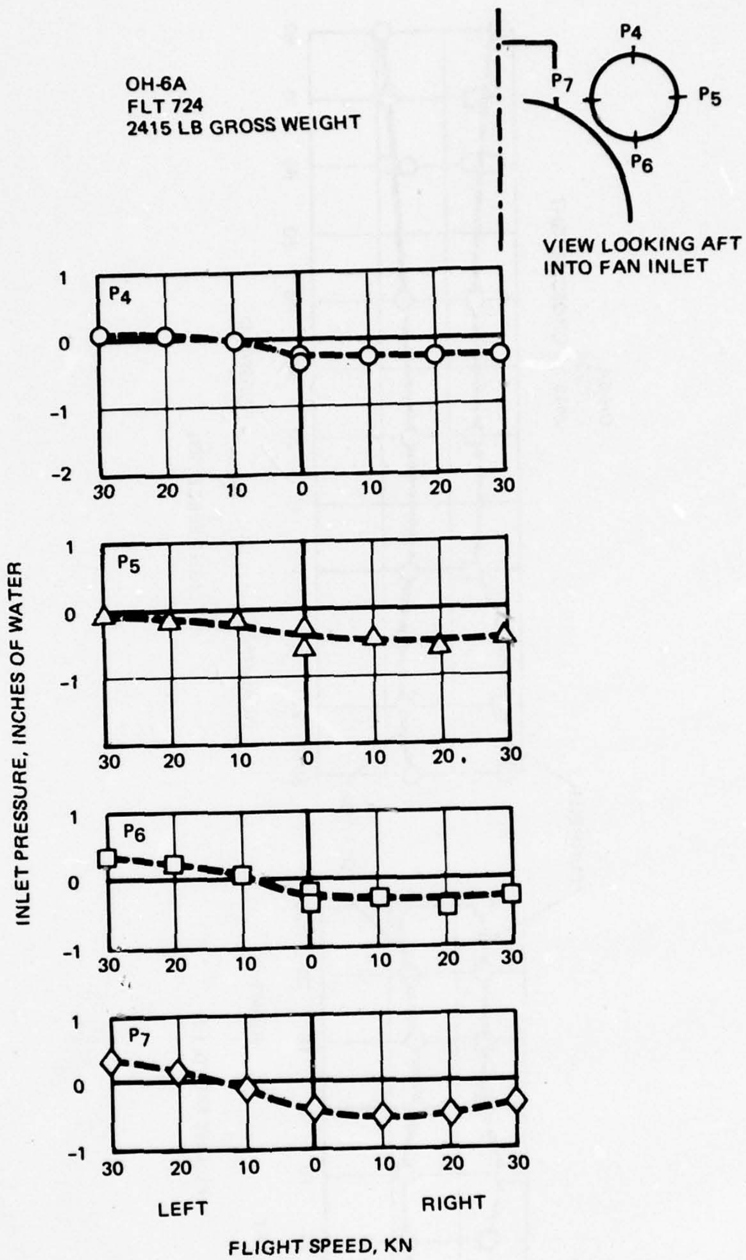
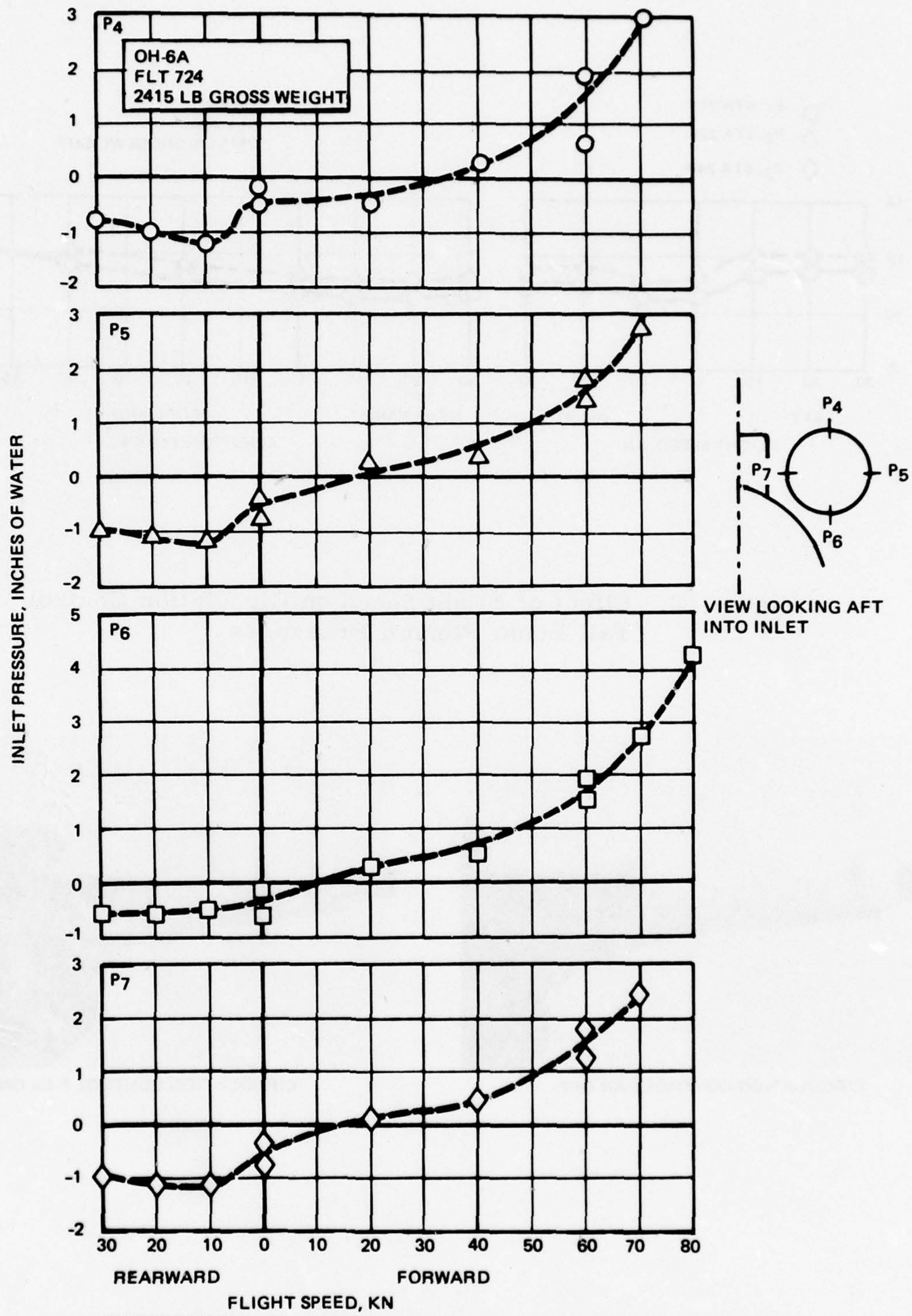


Figure 10. Effect of Flight Speed on Fan Current and Voltage.



a. EFFECT OF SIDEWARD FLIGHT SPEED ON FAN INLET PRESSURES

Figure 11. Effect of Flight Speed on Fan Inlet Pressure (Sheet 1 of 2).



b. EFFECT OF FORWARD AND REARWARD FLIGHT ON FAN INLET PRESSURES

Figure 11. Effect of Flight Speed on Fan Inlet Pressure (Sheet 2 of 2).

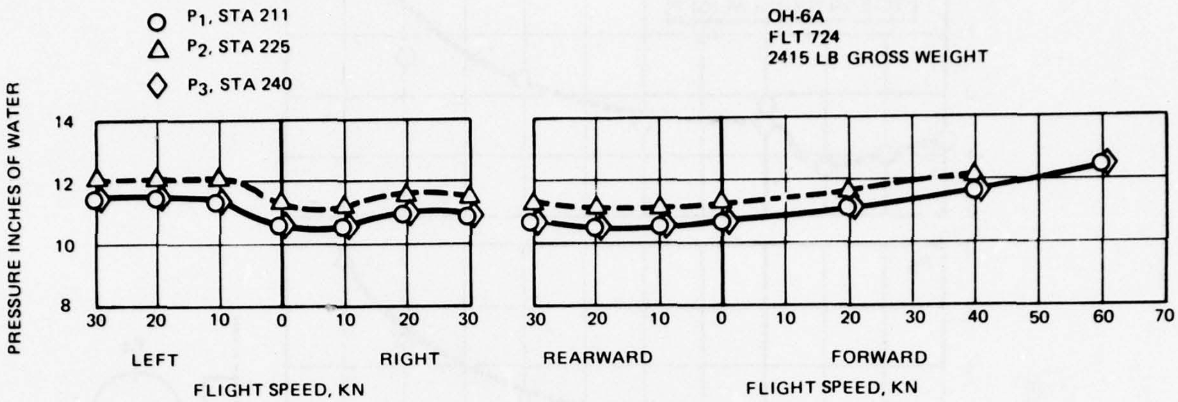
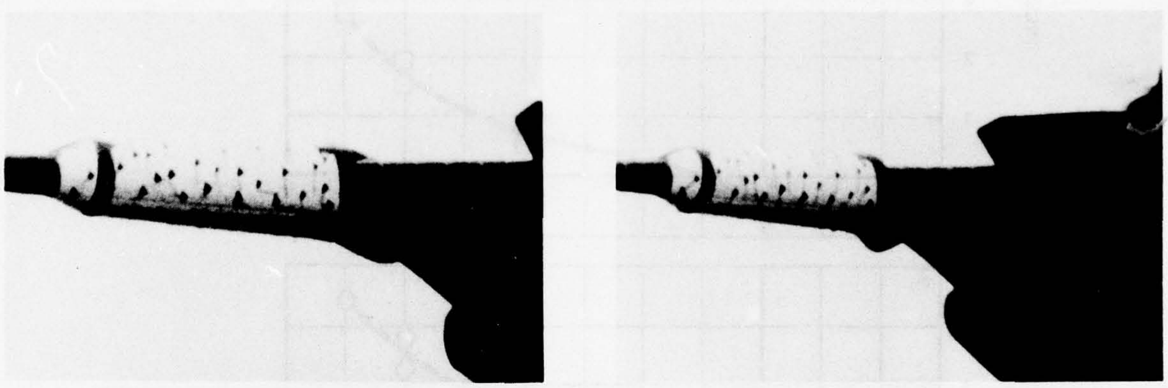


Figure 12. Effect of Flight Speed on Circulation Control Tail Boom Plenum Pressures.



CIRCULATION CONTROL FAN OFF

CIRCULATION CONTROL FAN ON

Figure 13. Flow Visualization of Circulation Control Effect.

right view of Figure 13. Here, the tufts show no evidence of separation either upstream or downstream of the slot. One characteristic is that the tufts are now stretched across the slot while in the left hand picture they are not. This change in flow quality corresponded with the successful generation of an antitorque force. When the circulation control tail boom produced force, the tufts showed no separation and resembled the flow quality shown in the right view of Figure 13. When no force was being generated, separation upstream of the slot was evident and the flow quality resembled the left view of Figure 13.

SIDEWARD FLIGHT

The reduction in tail rotor thrust due to circulation control was measured by one direct and two indirect methods. Tail boom lateral bending at Station 270 was a direct measurement. Tail rotor drive shaft torque and pedal position were the two indirect methods. During evaluation of circulation control effectiveness, all three measurements agreed qualitatively.

The tail boom lateral bending data recorded during flight test is presented in Figure 14. Variation in hover data was due to the difficulty of repeating exactly, over several flights, the aircraft gross weight, height, and control positions. Main rotor shaft torque was recorded during the test with the intent of correcting the data for variations in these parameters, but no consistent method could be found to reduce data scatter. Consequently, the data is presented as recorded.

The effect of circulation control on tail boom lateral bending at Station 270 is shown in Figure 14 by comparing the fan-off and fan-on conditions. The fan-off condition is the basic condition and behaves as expected. The boom bending generally lessens with sideward flight speed as the main rotor power requirements lessen. This behavior is typical of the OH-6A symmetrical tail rotor. The fan-on condition includes the influence of the circulation control tail boom. With reference to the fan-off condition, there is a sharp reduction in boom bending in hover and the reduction diminishes as 30-knot sideward flight speeds are approached. In hover, the lateral bending is reduced by approximately 480 inch-pounds, equivalent to 40 pounds of tail rotor thrust. The 40 pounds of equivalent tail rotor thrust means that the circulation control tail boom generated a wing lift coefficient of approximately 3.4.

The same general effect of circulation control can be seen in the tail rotor drive shaft torque data presented in Figure 15. The data are presented uncorrected for the reasons presented previously. By comparing the fan-off and fan-on conditions, a sharp reduction in torque is shown in hover and the reduction diminishes as flight speed increases. In hover, circulation control causes a 260-inch-pound reduction in torque which is equivalent to a reduction of 8.7 horsepower required by the tail rotor.

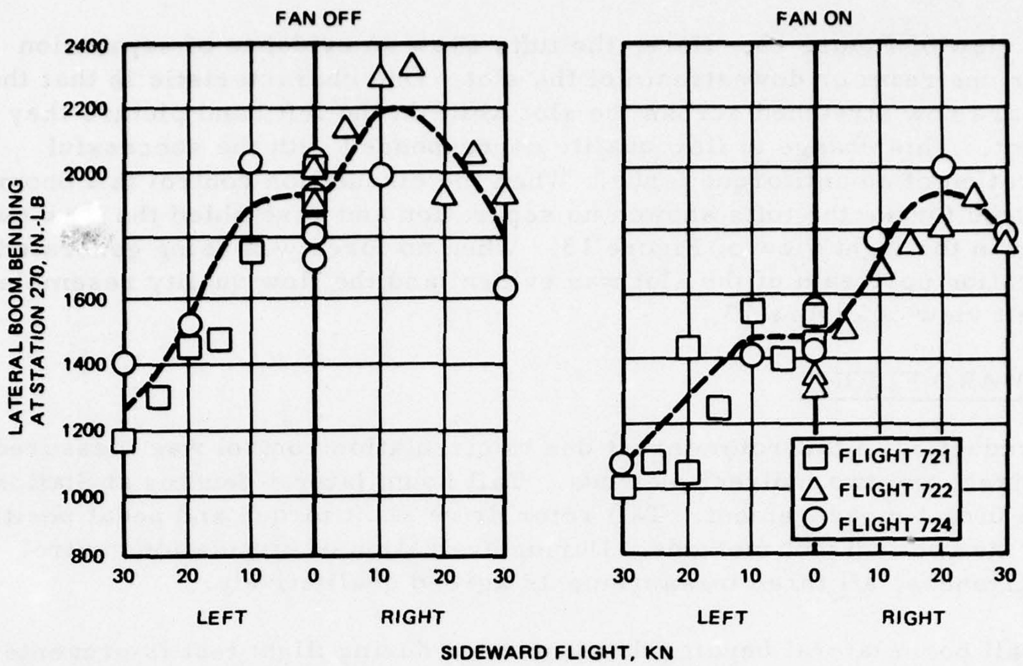


Figure 14. Tail Boom Bending at Station 270 Measured in Sideward Flight.

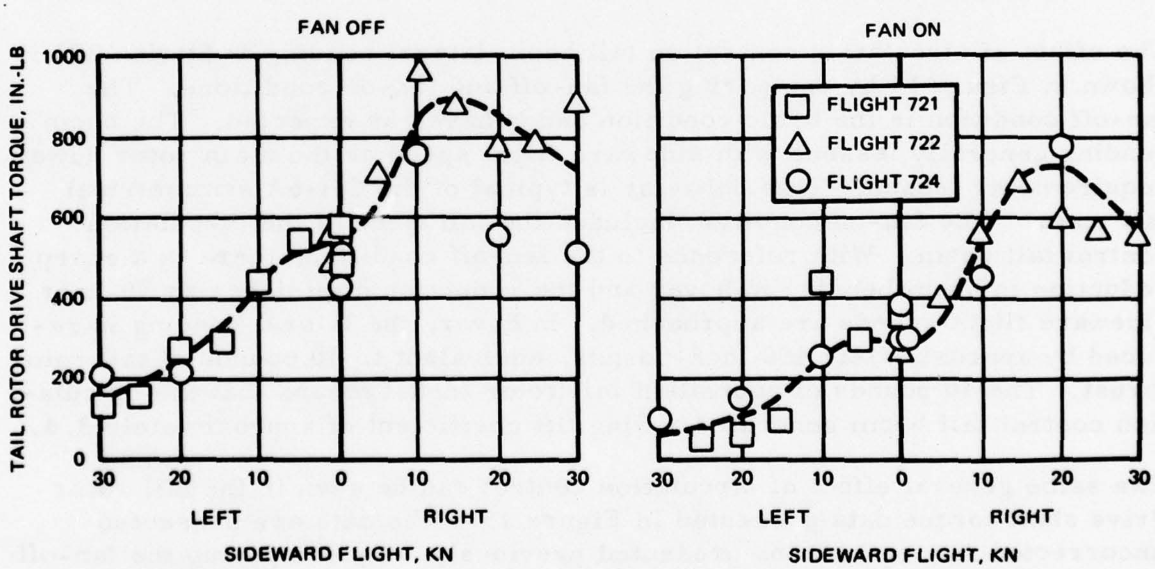


Figure 15. Tail Rotor Drive Shaft Torque Measured in Sideward Flight, $\Omega_{T/R} = 2107$ rpm.

The tail rotor thrust and power reductions due to circulation control in sideward flight are shown in Figure 16. In this figure, general curves were fitted through the boom bending and drive shaft torque data and the differences between the curves calculated. The boom bending has been converted to tail rotor thrust and the drive shaft torque converted to power. These figures show that circulation control, in hover, reduces the tail rotor thrust by 25 percent and the tail rotor power by 48 percent. With sideward flight speed, the effectiveness of the circulation control tail boom (as measured by thrust and power reductions) diminishes. This is due to the main rotor wake moving off the boom and the wake velocities diminishing in magnitude. In addition, the wake strikes the boom at a nonvertical angle which results in the circulation control force not being aligned with the horizontal tail rotor thrust. This effect can also be seen in the position of the flight controls.

The effect of circulation control on the flight controls in sideward flight is shown in Figure 17. Pedal position is presented as a percent from full left. Consequently, an increase in this percentage means more right pedal or a decrease in tail rotor thrust. With the fan on, pedal position has been shifted to the right by approximately 5 percent at all flight speeds. This shift to right pedal and the implied reduction in tail rotor thrust agrees with the tail boom bending and drive shaft torque data.

Longitudinal control position is presented as a percent from full aft control. An increase in this percentage represents an increase in download on the tail boom. As can be seen in Figure 17, turning the circulation control tail boom fan on causes no appreciable change in hover longitudinal control but does increase longitudinal control in right sideward flight and decrease it in left sideward flight. This is caused by a change in the orientation of the circulation control tail boom lateral force vector. In hover, this vector is approximately horizontal, normal to the main rotor downwash direction. In right sideward flight, the lateral force vector is directed downward because of the wake skew angle. This additional download (compared to the fan-off condition) is seen as more forward longitudinal control. In left sideward flight, the circulation control lateral force vector is now directed upward, producing a relative upload on the tail. This is seen as more aft longitudinal control.

Lateral control is presented as a percent from full right control. The effect of circulation control is evident. With the circulation control tail boom fan on, less lateral control is needed to direct the helicopter to the right or left. This is due to the reduction in tail boom drag caused by circulation control.

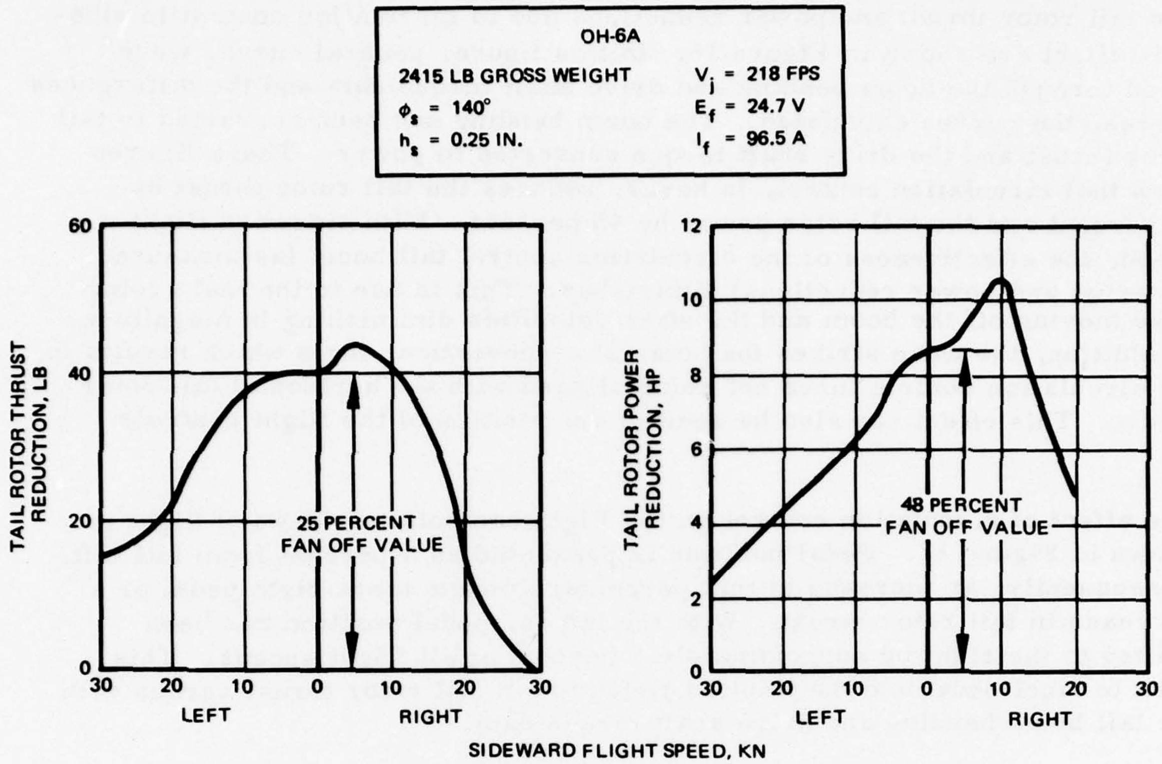


Figure 16. Tail Rotor Thrust and Power Reduction due to Circulation Control in Sideward Flight.

REARWARD/FORWARD FLIGHT

The effect of the circulation control tail boom on tail boom bending at Station 270 and tail rotor drive shaft torque is shown by comparing fan-on and fan-off conditions in Figures 18 and 19, respectively. There is some variance in the forward flight bending data due to the absence of the horizontal and vertical stabilizers. Without the stabilizers at higher forward speeds, it was difficult to maintain the same yaw angle between flight conditions. The changing yaw angle added a fuselage moment to which the tail rotor reacted, affecting the bending moment. However, this effect only occurred at higher speeds beyond the point at which circulation control became ineffective. The general trends are unaffected.

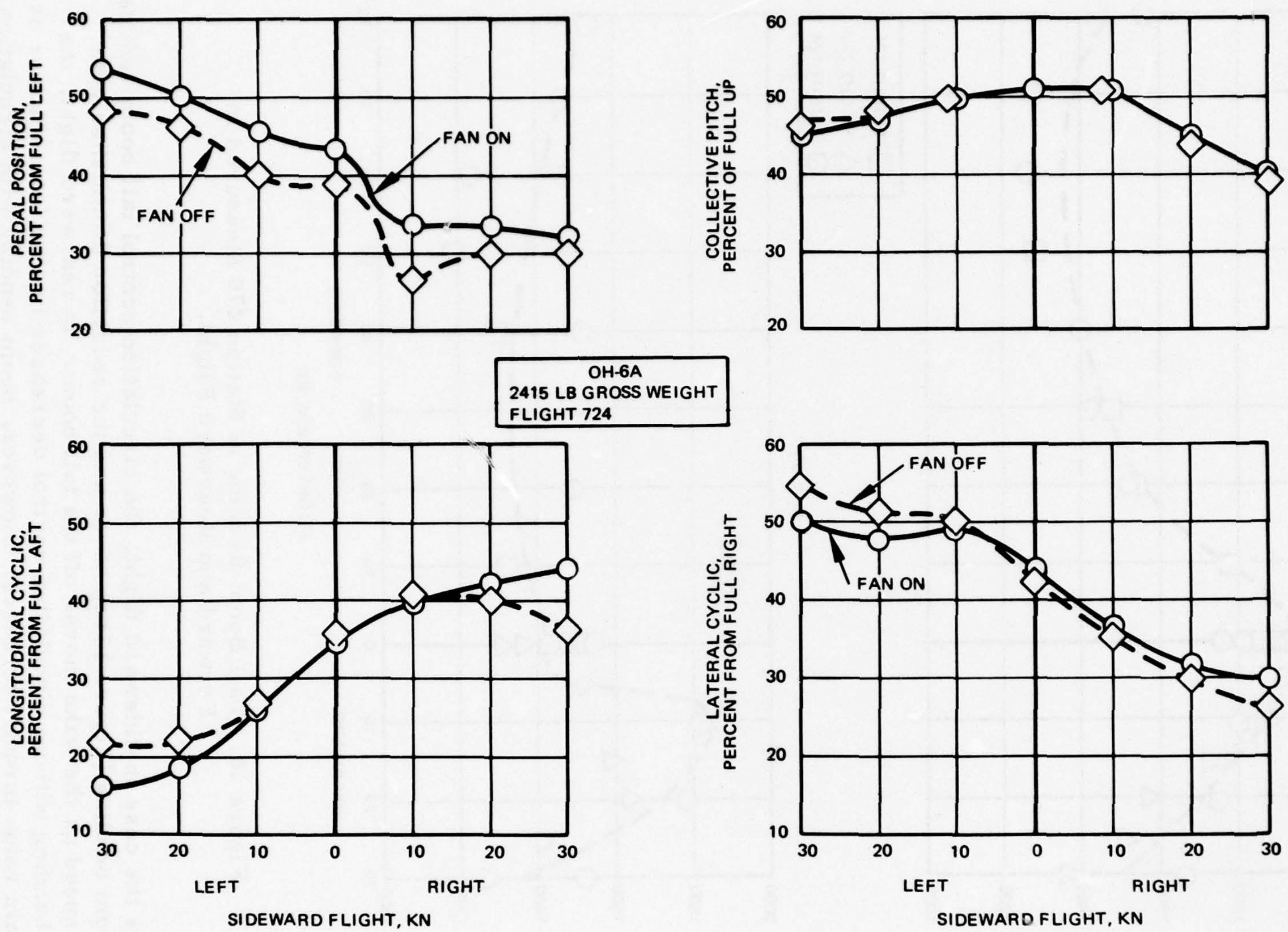


Figure 17. Effect of Circulation Control on Flight Controls in Sideward Flight.

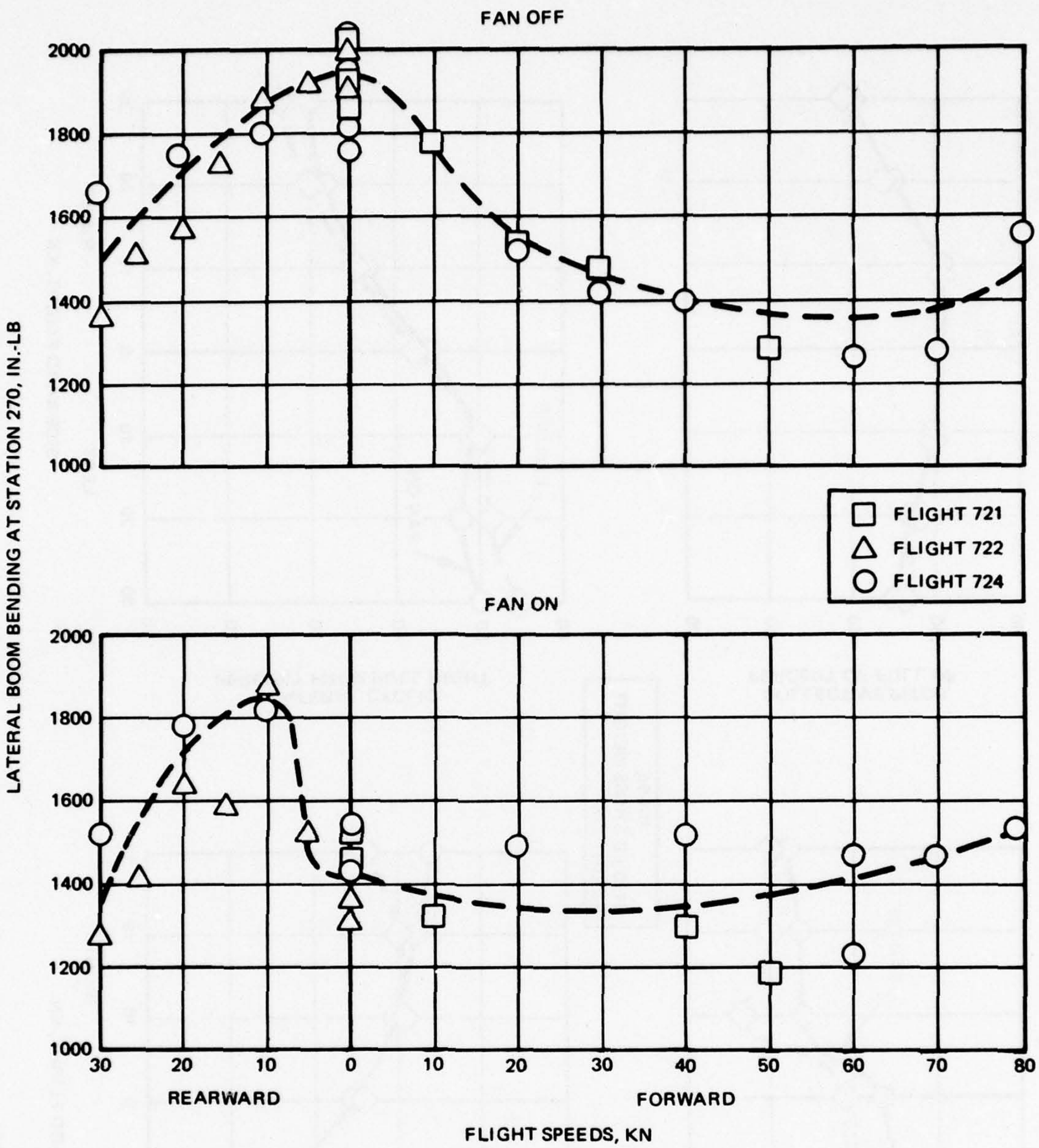


Figure 18. Tail Boom Bending at Station 270 Measured in Forward and Rearward Flight.

As was the case in sideward flight, the circulation control tail boom reduces the boom bending (Figure 18) in hover and the reduction diminishes with flight speed as the wake moves off the tail boom. In rearward flight, the boom bending without circulation control decreases in a uniform manner as the main rotor torque decreases. However, boom bending with circulation control rises sharply at first, then decreases uniformly. This behavior is

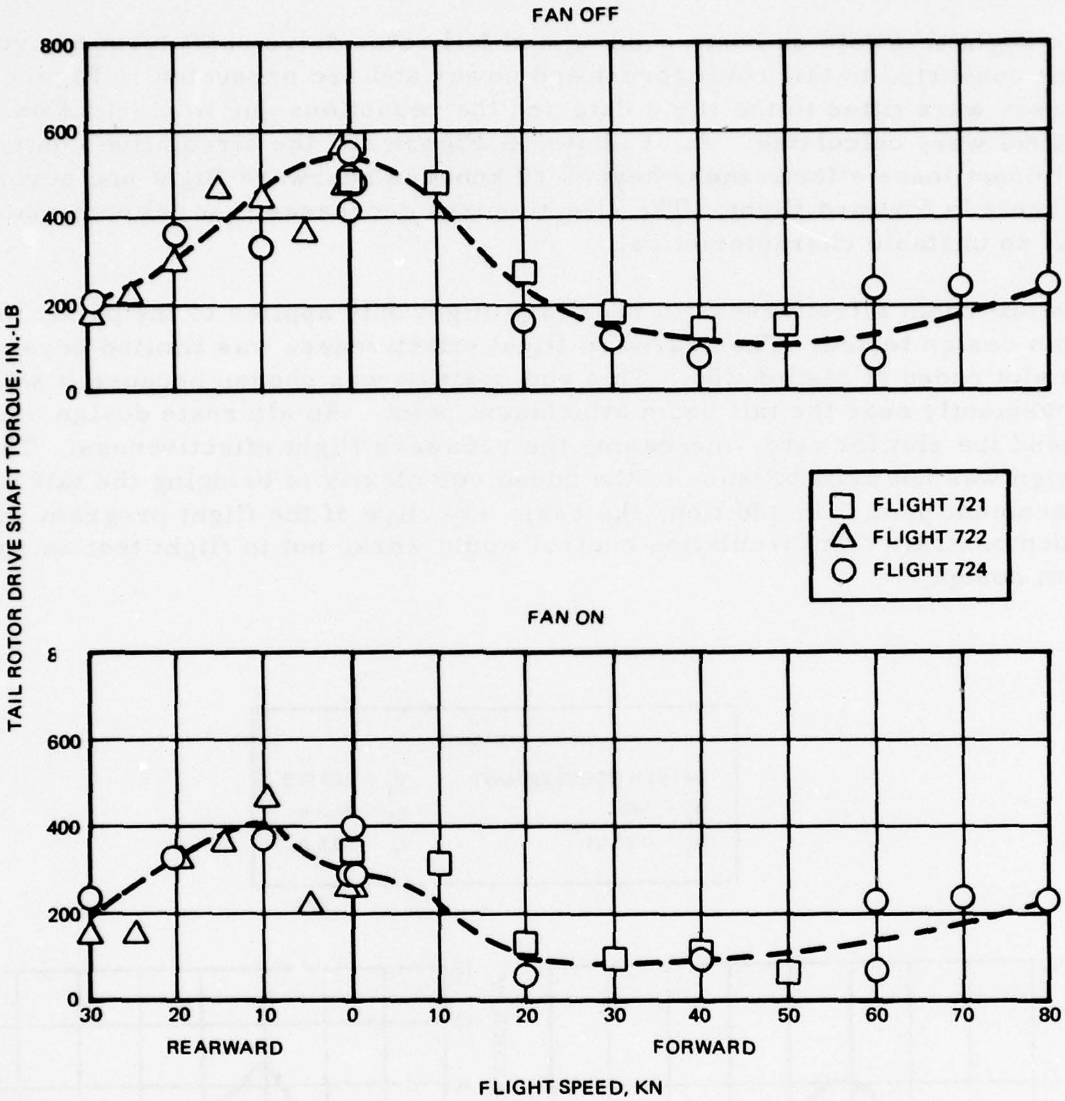


Figure 19. Tail Rotor Drive Shaft Torque Measured in Forward and Rearward Flight, $\Omega_{T/R}$ = 2107 rpm .

a consequence of the main rotor wake moving off the tail boom faster with rearward speed, rather than the reduction in main torque.

The effect of the circulation control tail boom on tail rotor drive shaft torque is shown in Figure 19. Again, the largest effect is shown in hover and it diminishes with flight speed. The drive shaft torque data also show the same behavior in rearward flight as did the boom bending. The fan-off data decreases uniformly while the fan-on data rises at first, then decreases with rearward speed.

The flight test data on boom bending and tail rotor drive shaft torque have been converted to tail rotor thrust and power and are presented in Figure 20. Curves were fitted to the flight data and the reductions due to circulation control were calculated. As is shown in Figure 20, the circulation control tail boom loses effectiveness beyond 10 knots in rearward flight and beyond 40 knots in forward flight. The effectiveness decreases in a uniform manner with no unstable characteristics.

The tail boom effectiveness in rearward flight only applies to the particular boom design tested. The rearward flight effectiveness was limited because the slot ended at Station 200. This end position was chosen because it was conveniently near the tail boom attachment point. An alternate design could extend the slot forward, increasing the rearward flight effectiveness. This design was not used because of the added complexity of bridging the tail boom attachment point. In addition, the basic objective of the flight program was to demonstrate that circulation control would work, not to flight test an optimum design.

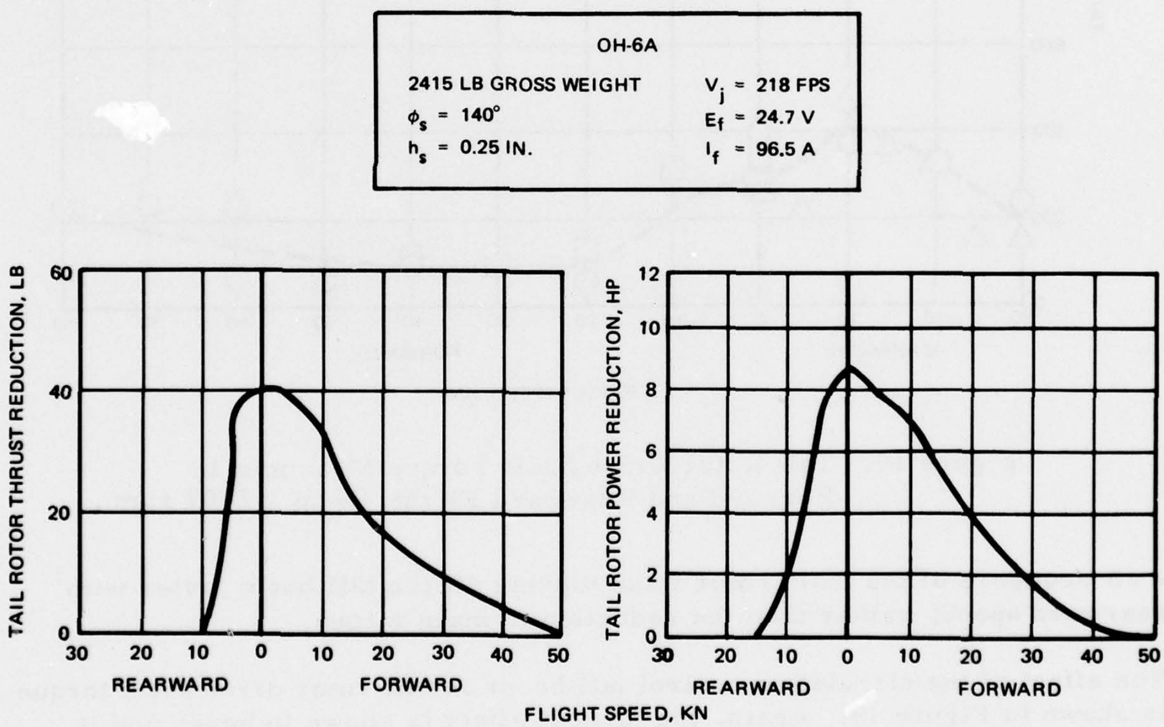


Figure 20. Tail Rotor Thrust and Power Reduction due to Circulation Control in Rearward/Forward Flight.

The effect of circulation control on flight controls in rearward/forward flight is show in Figure 21 by comparing fan-off and fan-on conditions. There is no significant change in collective or longitudinal control due to circulation control. There is some variation in controls position at high forward speeds due to the removal of the stabilizers.

In hover, pedal position shifts approximately 5 percent due to circulation control. This shift diminishes with flight speed. Lateral cyclic control is unchanged by circulation control with forward speed, but shifted in rearward flight. With the circulation control fan on, more right lateral cyclic control is required. The lateral cyclic shift is zero in hover, increases to 6 percent at 20 knots rearward flight, and decreases to 2 percent at 30 knots.

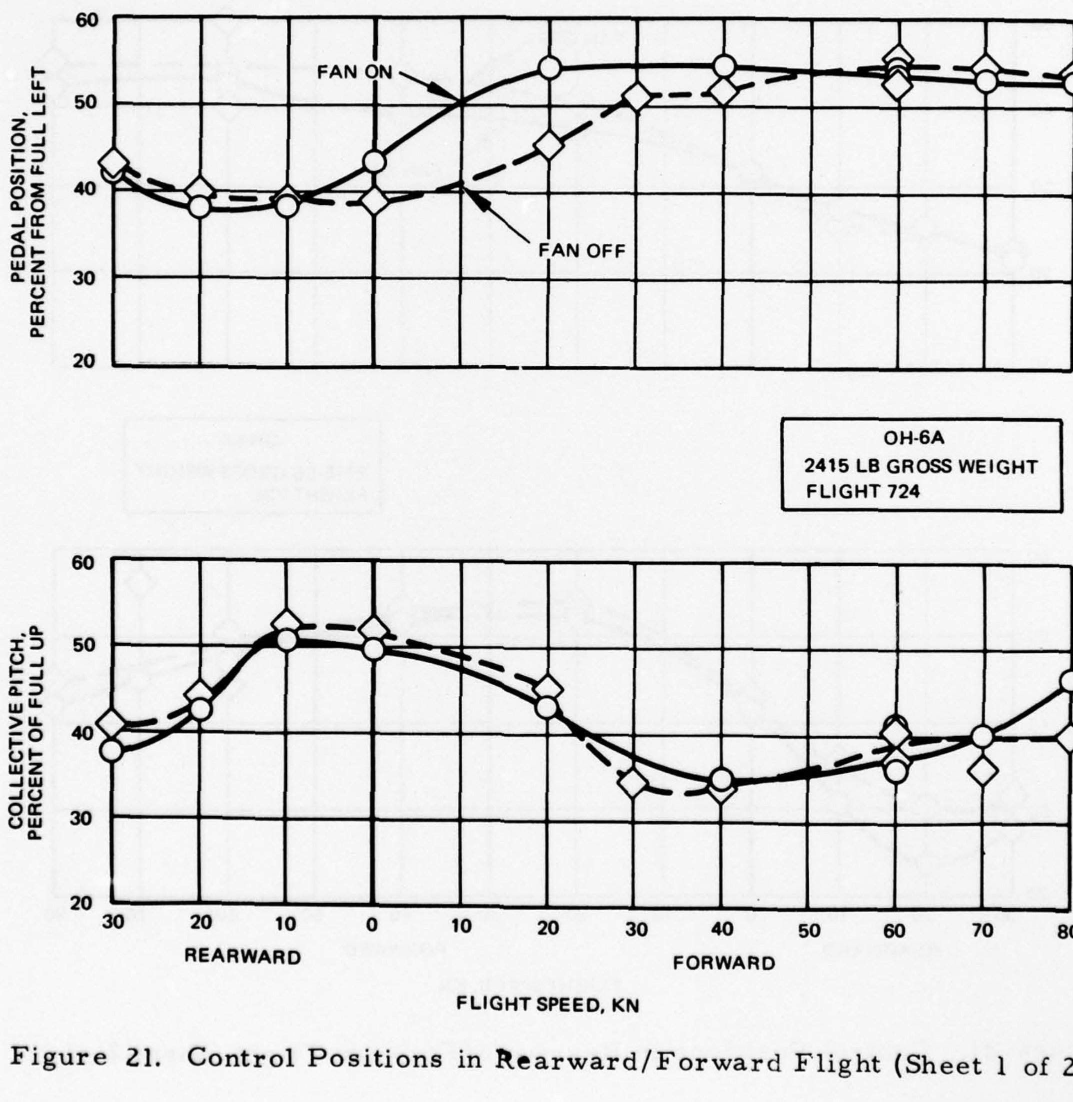


Figure 21. Control Positions in Rearward/Forward Flight (Sheet 1 of 2).

MANEUVER FLIGHT

The effect of the circulation control tail boom on maneuvers was investigated from hover to forward speed.

At the trimmed flight conditions in sideward and rearward/forward flight, there was no significant change in handling qualities caused by the circulation control tail boom. In right sideward and rearward flight, it was reported that there were larger excursions in yaw and pitch with circulation control blowing than without it. However, a review of the recorded data did not indicate any significant change.

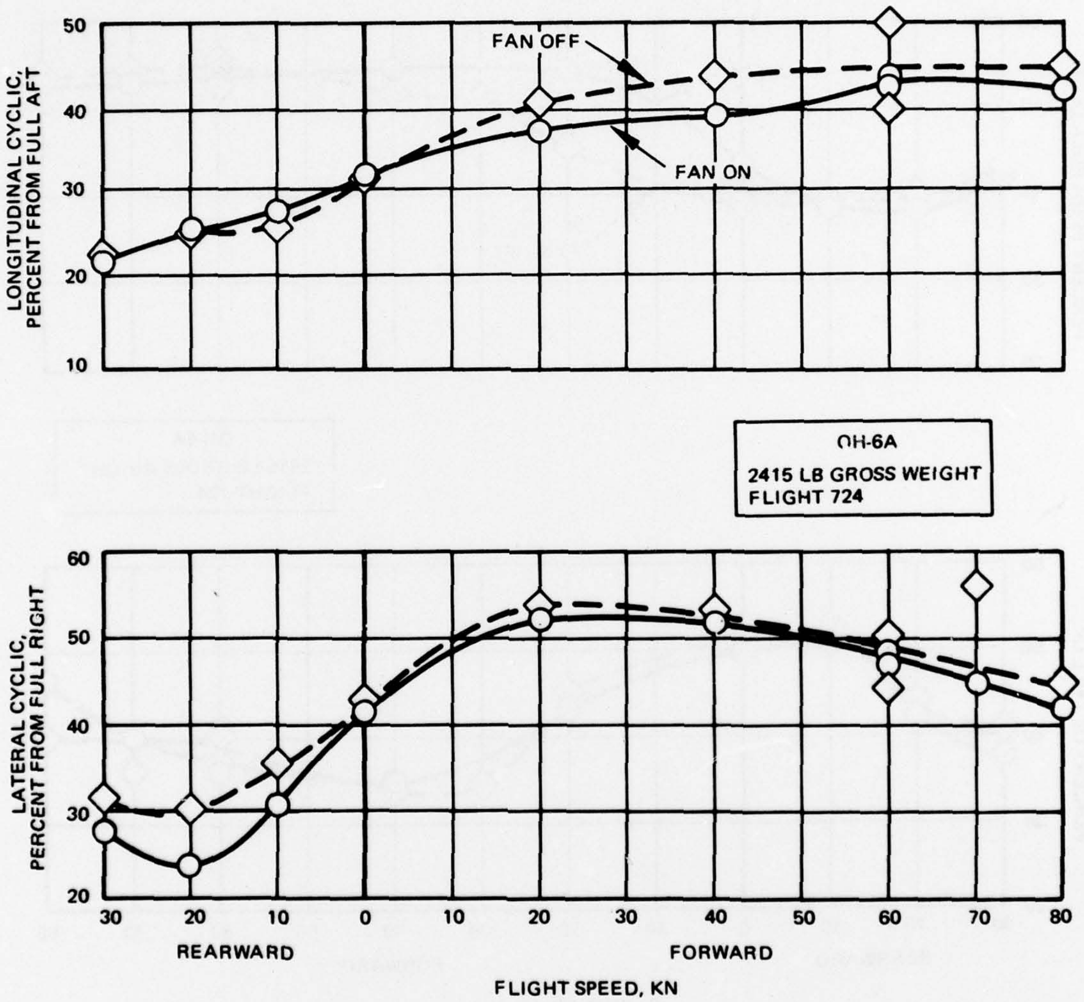


Figure 21. Control Positions in Rearward/Forward Flight (Sheet 2 of 2).

Vertical rate of climb was increased noticeably with circulation control fan on. Because of instrumentation failure, the increase in vertical rate of climb cannot be quantified, but there is qualitative agreement on the increase between the pilot, airborne observer, and ground observers.

The critical azimuth could not be identified for either the fan-on or fan-off condition. This was due to the removal of the stabilizers. The critical azimuth is the yaw attitude at which the heading cannot be held with increasing forward speed.

The effect of the circulation control tail boom on maneuver flight was explored at 60 knots. The objective of the investigation was to evaluate the effect of wake movement on and off the tail boom. The flight speed of 60 knots was chosen as a compromise between a flight speed high enough to generate significant load factors and low enough to approximate the speed at which circulation control becomes ineffective.

The flight test showed that the circulation control tail boom had little effect on the aircraft handling qualities in both conditions. Without the stabilizers, the aircraft handling qualities were generally poor at 60 knots.

This portion of the flight program was not meant to be all inclusive. A larger flight evaluation is needed to answer all questions. The flight program does indicate that the circulation control tail boom is stable.

TOTAL AIRCRAFT POWER

The total aircraft power required with and without circulation control is presented in Figure 22. Total aircraft power is the sum of main rotor power, tail rotor power, and fan power. Main rotor power is calculated using measured main rotor shaft torque, tail rotor power is calculated using measured tail rotor drive shaft torque, and fan power is electrical power caculated from measured current and voltage. The fan power is the power input to circulation control. As is shown in Figure 22, total hover power is reduced by 5.5 horsepower with circulation control. As flight speed increases in any direction, the power reduction diminishes. However, due to a reduction in main rotor power required with flight speed, the total power diminishes with flight speed for both the fan-on and fan-off conditions.

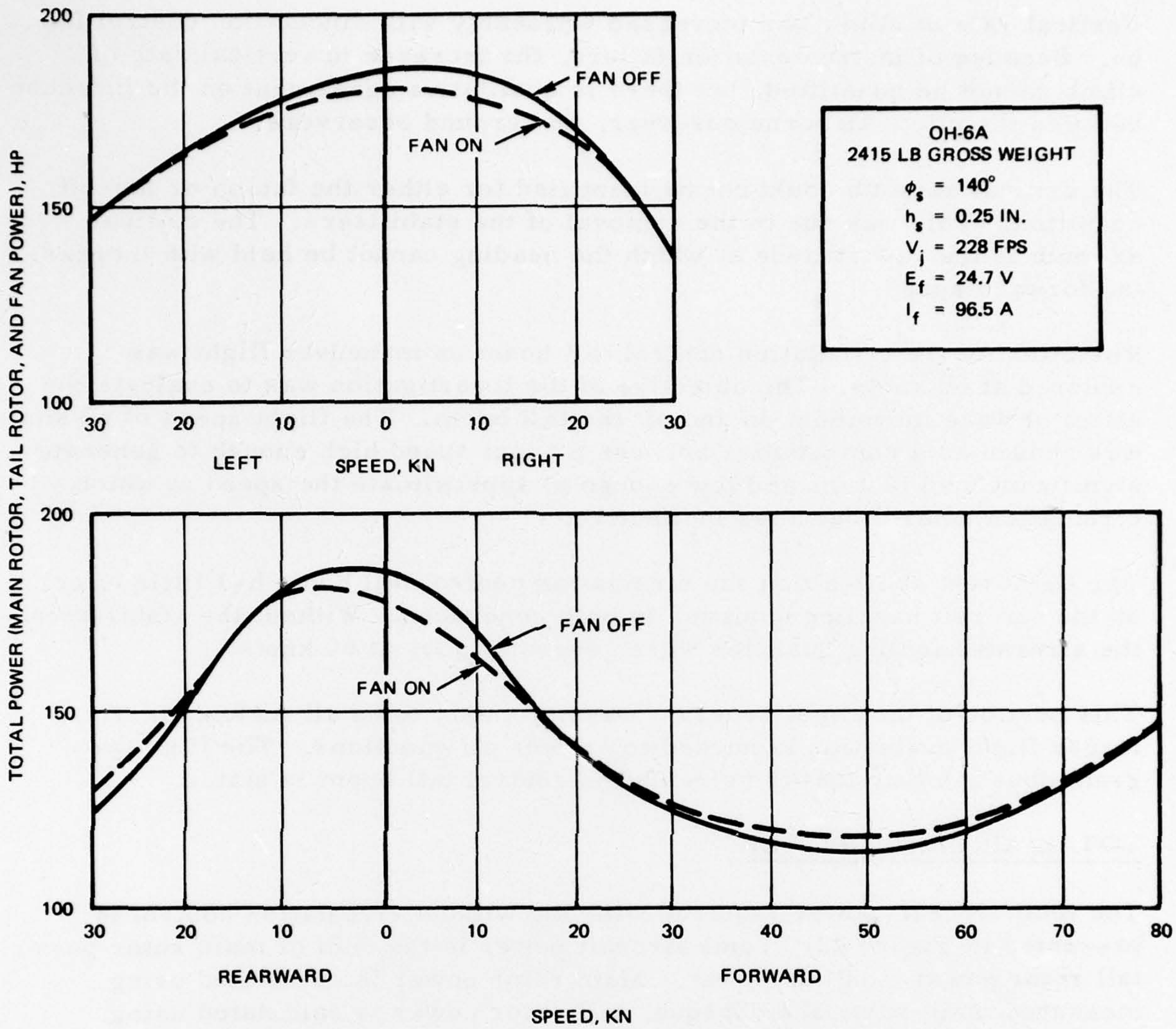


Figure 22. Total Power for Fan-Off and Fan-On Conditions.

The total hover power reduction is calculated by subtracting the fan electrical power (fan power = $E_f I_f$ = 3.2 HP) from the tail rotor power reduction (8.7 HP) in hover shown in Figures 16 and 20. The main rotor power in hover was not changed by the operation of the fan. As shown in Figures 17 and 21, the main rotor controls (collective, longitudinal cyclic, and lateral cyclic) in hover were not changed by fan operation, indicating no change in power required.

COMPARISON TO PREDICTION

The flight test tail rotor thrust reduction was compared to predicted values in both sideward and rearward/forward flight. The predicted values were calculated using a strip-integration procedure which combined wind tunnel lift and drag data on circulation control cylinders,[1] the tail boom geometry, and either measured downwash in hover or predicted downwash in flight. The downwash was predicted using simple wake momentum procedures similar to those of Reference 8. The predicted hover thrust was corrected using the whirl stand experimental measurements from Reference 7.

The predicted and measured tail rotor thrust reductions are presented in Figure 23 for both sideward and rearward/forward flight conditions. In sideward flight, there is general agreement at speeds beyond 10 knots in both lateral directions. In rearward/forward flight, the analysis predicts larger forces than measured.

In hover, the flight test circulation control tail boom produces approximately two-thirds of the expected thrust that was measured on the whirl stand with the same tail boom configuration. Initially it was felt that the reduction in hover efficiency was due to either a reduction in slot angle caused by aircraft roll or a reduction in jet velocity. The whirl stand design data, shown in Figures 7 and 8, demonstrate that the small reductions in these parameters would cause large changes in circulation control effectiveness. However, a check of these parameters indicated that this was not the case. Roll data indicate that the aircraft hovered repeatedly in a level attitude. Several independent measurements of jet velocity and circulation control tail boom pressure verified the recorded data. It is now felt that the reduction is caused by a subtler effect.

The reduction in hover efficiency is caused by a small increase in wake velocities between the whirl stand and the flight test. An OH-6A main rotor was used in both tests and the boom orientation was identical. It is felt that the blade tracking stand provided some interference which was not seen in the flight program.

This particular circulation control tail boom was sensitive to changes in downwash due to the unique Reynolds number range in which it operated. Figure 24 presents the effects of Reynolds number on circular cylinder drag.[9] As can be

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[8] Heyson, H. H., KATZOFF, INDUCED VELOCITIES NEAR A LIFTING ROTOR WITH NONUNIFORM DISK LOADING, National Advisory Committee Aeronautics Technical Report 1319, 1957.

[9] Schlichting, H., BOUNDARY-LAYER THEORY, 6th Edition, McGraw-Hill, 1968.

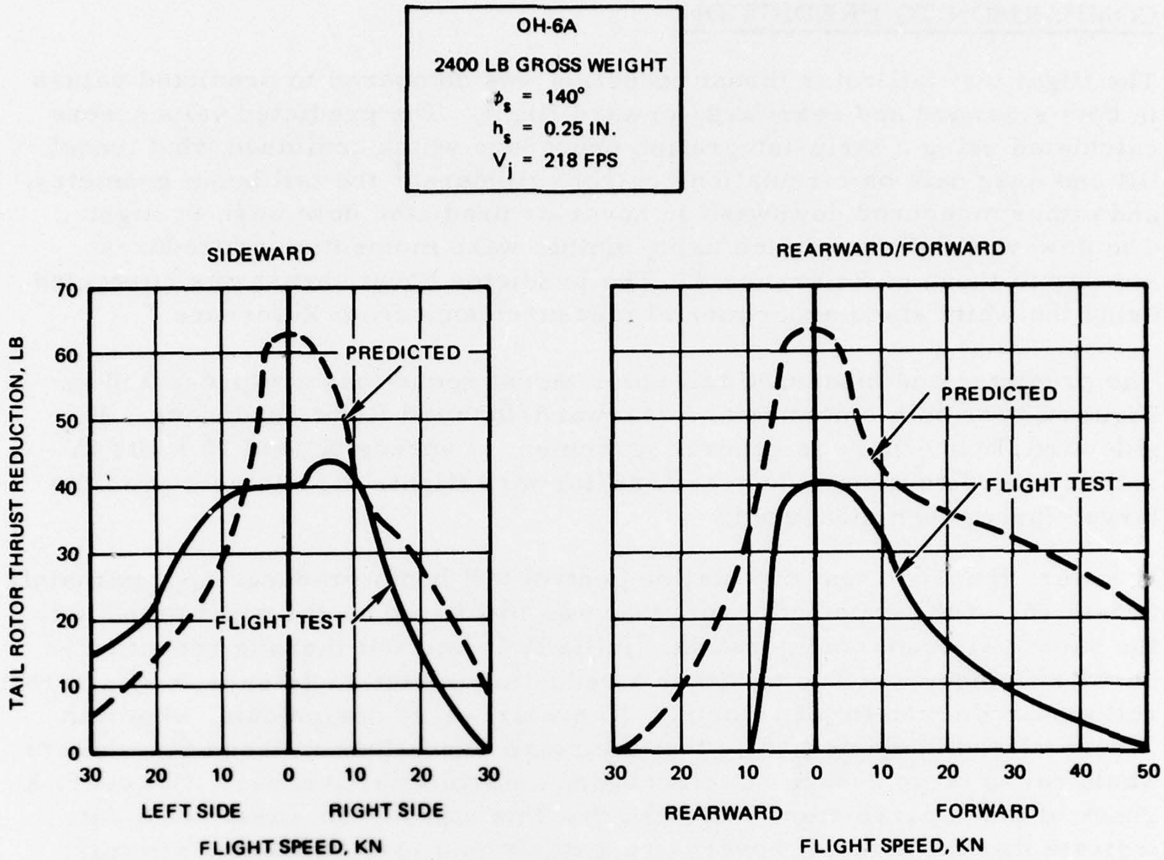

Figure 23. Predicted and Measured Tail Rotor Thrust Reduction from Circulation Control.

seen, the whirl stand tests were at subcritical Reynolds numbers, but just on the threshold of transition to supercritical Reynolds numbers. Any increase in wake velocities would move the tail boom into supercritical conditions and cause a sharp change in surface flow conditions. This change in flow conditions is shown in Figure 25 where cylinder surface pressure is shown as a function of azimuth position around the circumference. At subcritical Reynolds numbers, the flow separates at approximately 90 degrees, while at supercritical Reynolds numbers, the flow separates at approximately 120 degrees.

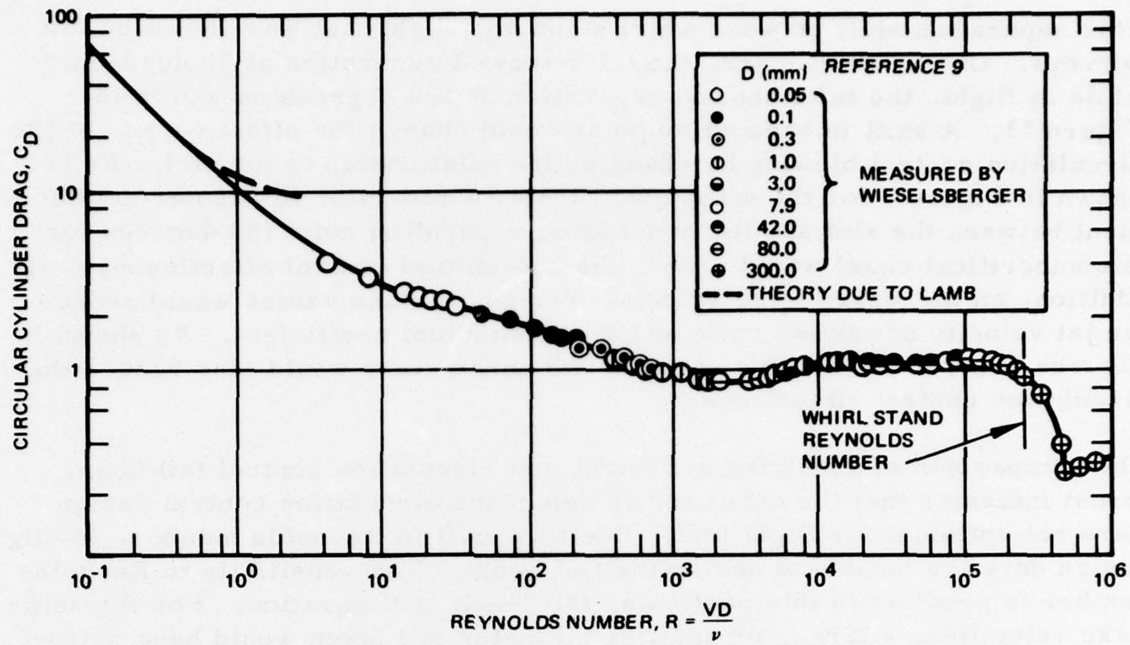

Figure 24. Circular Cylinder Drag Versus Reynolds Number.

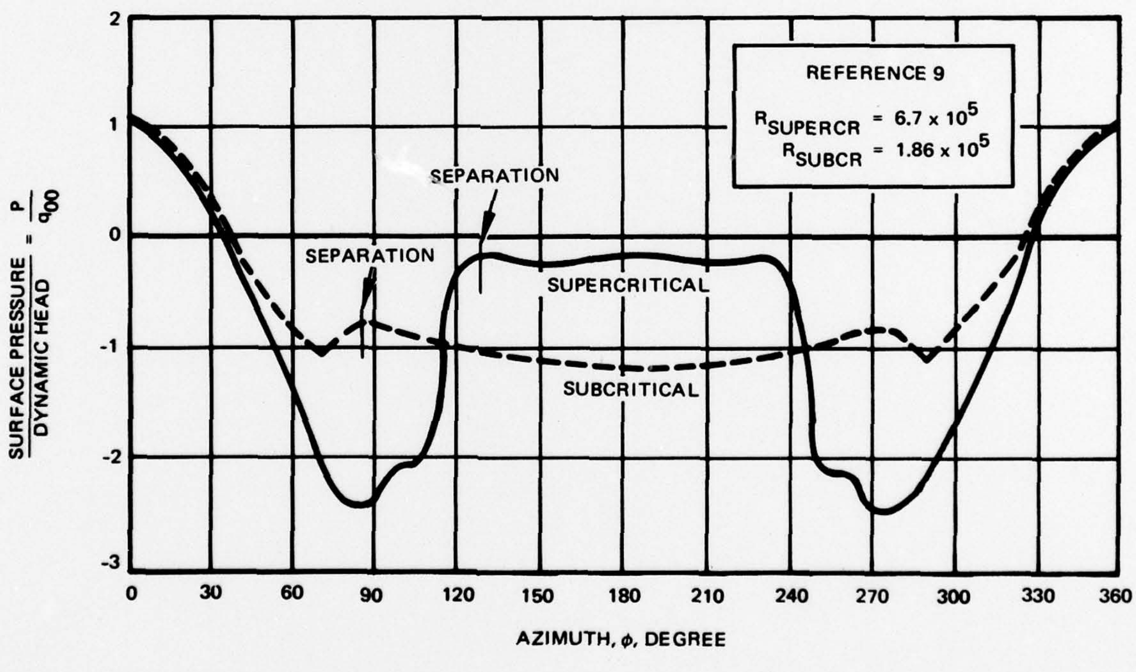

Figure 25. Circular Cylinder Pressure Distribution at Subcritical and Supercritical Reynolds Number.

This separation shift between whirl stand and flight test was shown by tuft surveys. On the whirl stand, the tufts showed separation at 90 degrees, while in flight, the tufts showed separation at 120 degrees as shown in Figure 13. A shift in separation point would change the effectiveness of the circulation control blowing by changing its relationship to the slot. As is shown in Figure 7 for the whirl stand tests, a reduction in angular displacement between the slot and the nonblowing separation point (90 degrees for this subcritical case) would reduce the circulation control effectiveness. In addition, an increased wake velocity over whirl stand values would reduce the jet velocity downwash ratio and the momentum coefficient. As shown in Figures 8 and 9, reductions of these two parameters would also reduce the circulation control effectiveness.

The comparison of predicted and flight test circulation control tail boom thrust indicates that the data used to select the circulation control design were not optimum for flight test. Due to a shift in Reynolds number, in-flight design data are needed to design the tail boom. The sensitivity to Reynolds number is peculiar to this particular tail boom configuration. For the same wake velocities, a larger or smaller diameter tail boom would have shifted the Reynolds number sufficiently to avoid the critical area. In addition, a tail boom shape other than circular would have shifted the critical Reynolds number.

APPLICATION OF CIRCULATION CONTROL TAIL BOOM

The circulation control tail boom can be used advantageously both with and without a tail rotor. When used with a tail rotor it acts as a supplemental antitorque device which unloads the tail rotor. Used in this manner, the circulation control tail boom would reduce the power required to react to antitorque moment, thus providing more power to the main rotor. This could be translated into higher hover gross weight and greater vertical rate of climb. The disadvantages would be the installation of an additional fan to provide the circulation control air. The fan could be driven by a belt attached to the present tail rotor drive shaft. A clutch could be installed to disengage the fan in flight conditions where circulation control is ineffective.

The circulation control tail boom can best be used in an integrated antitorque system which eliminates the helicopter tail rotor. The tail rotor is replaced with a system that combines circulation control along the boom and a direct-jet thruster (Figure 26). A variable-pitch fan is mounted within the fuselage and blows air axially along the tail boom, providing air for both circulation control and the direct-jet thruster. The circulation control tail boom provides the majority of the antitorque force in hover, with the direct jet providing the additional trim antitorque force as well as the maneuver force.

The circulation-control/direct-jet system has several advantages: reduced accidents, reduced ballistic vulnerability, and reduced personnel hazard. As an example of the benefits, 15 percent of all helicopter accidents are caused by the tail rotor. Of that 15 percent, half are caused solely by tail rotor strikes which will be eliminated by the circulation-control/direct-jet

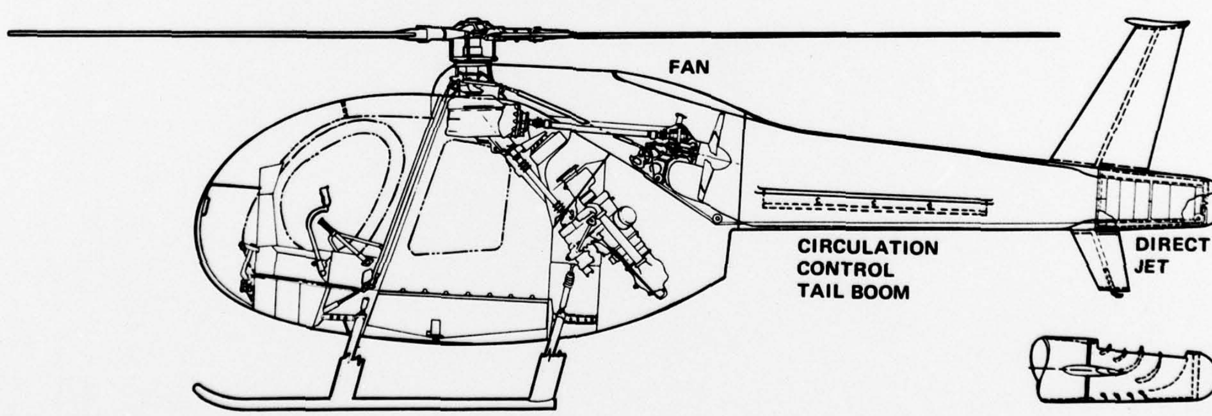

Figure 26. Design to Eliminate the Tail Rotor.

system. Ballistically, the circulation-control/direct-jet system virtually eliminates 50 to 100 percent of the area of a typical advanced attack helicopter that is vulnerable to explosive and API rounds. The elimination of high-speed, whirling, tail rotor blades has an evident contribution in the reduction of personnel hazards.

CONCLUSIONS

- Circulation control principles can be applied effectively to a helicopter tail boom to produce antitorque force from the main rotor wake.

- The circulation control tail boom interacted with the main rotor wake in a steady, controllable, and predictable manner.

- In hover, one circulation control tail boom configuration produced 40 pounds of equivalent tail rotor thrust and reduced tail rotor power by 8.7 horsepower. The equivalent tail rotor thrust and horsepower represent 25 and 48 percent of the no-blowing values, respectively.

- In maneuvering flight at 60 knots, the circulation control tail boom did not affect the handling qualities of the aircraft. The maneuvers included turns, pull-ups, push-overs, climbs, and autorotation.

- Including the fan electrical power, the helicopter required 5.5 less horsepower to hover with the circulation control tail boom operating than with it inoperative.

- Analysis of the flight test results indicates that the circulation control tail boom configuration tested was not optimum for flight test. A shift in Reynolds number between the whirl stand and flight test reduced the effectiveness of the circulation control configuration which was optimized on the basis of the whirl stand data. Changes in the configuration could produce more equivalent tail rotor thrust for the same power.

- Due to the limited extent of the circulation control slot, the circulation control tail boom loses effectiveness beyond 10 knots in rearward flight. The effectiveness decreases in a uniform manner with no unstable characteristics.

- With sideward flight speed, the effectiveness of the circulation control tail boom diminished due to the main rotor wake moving off the boom and the wake velocities diminishing in magnitude.

RECOMMENDATIONS

- Other circulation control tail boom configurations should be flight-tested to expand the design data base. The additional configurations should include changes in slot angle, slot extent, number of slots, momentum coefficient, and jet velocity.
- A program should be started to develop a prototype helicopter which combines the circulation control tail boom with a direct jet in a yaw control system that eliminates the tail rotor.

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SYMBOLS

Symbol	Definition
C_D	Circular cylinder drag coefficient
C_μ	Momentum coefficient = $2\left(\frac{\rho_j}{\rho_\infty}\right)\left(\frac{V_j}{W_{max}}\right)^2 \frac{h_s}{D_B}$
D	Cylinder diameter
D_B	Mean tail boom diameter
E_f	Fan voltage
h_s	Slot width
I_f	Fan current
P	Surface pressure
q_∞	Free-stream dynamic pressure
R	Reynolds number = VD/ν
V	Free-stream velocity
V_j	Jet velocity
W_{max}	Maximum downwash in plane of the boom
θ_{75}	Main rotor collective pitch at three-quarters of blade radius
ν	Kinematic viscosity
ρ_j	Jet density

SYMBOLS (CONT)

Symbol	Definition
ρ_{∞}	Free-stream density
ϕ	Azimuth angle measured from free-stream direction
ϕ_s	Slot angle measured from top centerline of tail boom
$\Omega_{T/R}$	Tail rotor drive shaft speed